The Pennsylvania State University

The J. Jeffrey and Ann Marie Fox Graduate School

A USER-CENTERED APPROACH TO HAPTIC INTERFACE DESIGN

A Thesis in

Informatics

by

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Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

May 2025

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ABSTRACT

Haptic interface design remains a relatively underdeveloped area of human-computer interaction, lacking the cohesive principles that guide visual or auditory interface design. This thesis addresses that gap by proposing a structured framework that categorizes haptic interactions into four interdependent domains: the domain of the natural, the domain of the physical, the domain of the virtual, and the domain of the artificial. Synthesizing haptics research across multiple academic disciplines, each domain is defined in terms of the principles governing its respective system (biological, mechanical, computer, or psychological) and its role in shaping haptic experiences. Building on this framework, a user-centered approach to haptic interface design is developed with a focus on satisfying key criteria—adaptability, meaningfulness, and immersion—for improving haptic feedback. Important HCI theories and design principles (e.g., Norman's usability principles, Gibson's affordance theory) are applied to ensure that haptic interfaces become intuitive, discoverable, and engaging. Overall, this thesis offers a cohesive design paradigm that bridges technical haptic research with user-centered design, yielding practical guidelines and heuristics for creating more effective and immersive haptic interfaces. This thesis not only advances the current theoretical understanding of haptic design, but also provides actionable insights for developing future haptic systems that better align with human perception and cognition.

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ACKNOWLEDGEMENTS

First and foremost, I would like to thank my thesis advisor Dr. Frank Ritter. His mentorship and support have been influential and integral not only to this thesis, but also to my growth as a scholar.

I am also sincerely grateful to Dr. Fred Fonseca. His guidance has helped shape this work, and without his encouragement I would never have pursued a master’s degree in the first place.

I would like to thank Dr. Stager for her thoughtful feedback and constructive suggestions to further expand my work.

To my parents, I owe more than words can express. Their unwavering support has been the foundation of my success, not only in this academic endeavor but in all aspects of my life.

Finally, I would like to thank my friends. Whether serving as sounding boards for ideas or offering companionship during this journey, their presence made the process not only manageable but enjoyable.

Chapter 1

Introduction: Haptics and Haptic Interfaces

Haptic interfaces, which provide touch-based feedback to users, are an essential yet underdeveloped aspect of human-computer interaction. While significant progress has been made in graphical and auditory interface design, haptic interfaces have not benefited from equivalent advancements, often remaining inconsistent, difficult to learn, and secondary to other interaction modalities. This disparity arises from fundamental challenges in haptic perception, the need for active exploration, and the absence of a standardized haptic lexicon that would enable clear and consistent interpretation of feedback. Although haptic feedback has been successfully integrated into various domains, including consumer electronics, virtual reality, robotics, and assistive technologies, its implementation remains fragmented. Current approaches often focus on isolated technical advancements without a cohesive theoretical framework guiding the design of haptic interactions in a way that ensures usability, adaptability, and immersion. The absence of such a framework limits the discoverability of haptic feedback and constrains its potential as a primary interaction modality in digital and physical interfaces.

In this thesis, I address a fundamental gap in haptic design theory by proposing a structured framework that categorizes haptic interactions into four distinct, yet interdependent domains: the domain of the natural, the domain of the physical, the domain of the virtual, and the domain of the artificial. This four-domain framework, which is the result of a comprehensive synthesis of existing haptic literature, provides a foundation for understanding how haptic interactions function across biological, mechanical, computational, and psychological dimensions. Applying this framework, I identify three key criteria for effective haptic interface design—adaptability, meaningfulness, and immersion—which ensure that haptic feedback is flexible, informative, and engaging for users. Using these criteria as a foundation, I develop a user-centered design approach to guide the creation of haptic interactions that align with human capabilities and expectations.

Several fundamental challenges have impeded the development of cohesive haptic design principles. First, unlike visual or audio interfaces, haptic systems lack well-defined affordances, so users often do not receive intuitive or consistent tactile cues. Because haptic feedback is not passively perceivable, users must actively explore through touch, which makes discoverability of features difficult. Moreover, there is no widely accepted haptic lexicon or grammar to standardize tactile signals, leading to inconsistent interpretations of similar feedback across devices. Together, these issues mean that users may struggle to understand and trust haptic feedback, limiting its effectiveness as a primary interaction modality.

By organizing haptic design within a structured model, I move beyond technical considerations to explore how haptic interfaces can be designed to enhance user experience in meaningful ways. Although prior research has extensively examined haptic perception and feedback, there remains a need for a design approach that bridges these studies with user-centered design principles. Through this structured examination, I contribute to the advancement of haptic interface design by offering a model and design approach that are both theoretically grounded and applicable to real-world interaction challenges.

Problem statement

Haptic interfaces remain an underdeveloped area within human-computer interaction despite their critical role in enhancing user experience through tactile and kinesthetic feedback.

While graphical and auditory interfaces have matured through well-defined design principles and standardized methodologies, haptic interfaces have not benefited from the same level of progression. This disparity is not due to a lack of technological advancements; in fact, haptic feedback has been integrated into a variety of domains, including consumer electronics, virtual reality, automotive safety, and robotic surgery (Culbertson, Schorr, & Okamura, 2018; Okamura, 2009). However, the absence of a unified framework for haptic design has led to fragmented development, where haptic feedback is often implemented as an afterthought rather than as an integral component of the interface.

The fundamental challenge in haptic design arises from three critical gaps in current research and implementation. First, haptic interfaces lack a structured framework that accounts for the full scope of human haptic perception, physical interactions, digital simulations, and cognitive interpretation. Unlike visual and auditory interfaces, which have clear affordances and design heuristics, haptic interfaces often fail to provide intuitive, discoverable, and meaningful feedback to users (Lederman & Klatzky, 1987; MacLean, 2000). Second, haptic interactions require active exploration rather than passive reception, making discoverability a persistent challenge. While a graphical interface provides visible cues and an auditory interface conveys information through sound, haptic interactions depend on physical engagement, making it difficult to establish consistent patterns for user guidance and expectation setting (Gibson, 1962; Srinivasan & Basdogan, 1997). Third, there is no widely accepted haptic lexicon or grammar to standardize feedback interpretation. Unlike the well-established linguistic structures in visual and auditory design, haptic signals lack an agreed-upon vocabulary, which creates inconsistencies in how users interpret tactile feedback across different systems and applications (Hayward & MacLean, 2007; MacLean, 2000).

This thesis addresses a fundamental gap in haptic design theory by synthesizing existing research into a structured framework that categorizes haptic interactions into four distinct, yet interdependent domains: the domain of the natural (biological principles), the domain of the physical (mechanical systems), the domain of the virtual (computational models), and the domain of the artificial (psychological and experiential factors). This framework provides a structured approach for understanding haptic interactions across multiple dimensions and serves as the foundation for developing a user-centered theory of haptic design. Applying this framework, I identify three key criteria—adaptability, meaningfulness, and immersion—that can improve the design of haptic feedback. With these criteria as a foundation, I leverage the four-domain framework to develop a user-centered approach to haptic design that distinguishes between artifact and feedback design. Overall, this thesis offers insights into how haptic interactions can be structured to better align with user expectations, resulting in more intuitive and discoverable haptic interfaces.

Contributions

This thesis makes several key contributions to the field of haptic interface design by synthesizing existing research into a structured framework and applying it to develop a user-centered approach for designing haptic interactions. First, I develop a structured framework which categorizes haptic design into four distinct, but interdependent domains: the domain of the natural (biological principles), the domain of the physical (mechanical systems), the domain of the virtual (computational models), and the domain of the artificial (psychological and experiential factors). This framework is the result of a comprehensive literature review and provides as a structured way to understand the different dimensions of haptic interaction. Unlike previous fragmented approaches, this framework integrates knowledge from multiple disciplines, providing a more cohesive understanding of how haptic interfaces function and can be designed effectively.

Second, building upon this framework, I identify three key criteria—adaptability, meaningfulness, and immersion—that can be leveraged to improve the design of haptic interfaces. These criteria are essential for ensuring that haptic feedback is not only functional, but intuitive, contextually relevant, and engaging. Adaptability refers to the system's ability to respond dynamically to user inputs and environmental changes, meaningfulness ensures that haptic feedback conveys useful and interpretable information, and immersion enhances user engagement by creating a sense of presence through tactile interaction.

Third, I apply the structured framework and the three identified criteria to develop a user-centered approach to haptic design. I identify several key challenges to haptic design and key considerations for designers as they seek to improve haptic interactions across various domains.

Fourth, within this approach, I distinguish between artifact and feedback design as fundamental aspects of haptic interface development. Artifact design refers to the structural and mechanical components of haptic systems, addressing how devices are physically designed to interact with users. Feedback design, on the other hand, focuses on how haptic responses are generated and perceived, ensuring that they align with user expectations and the context in which they are applied. Distinguishing between these two aspects of design provides a more nuanced understanding of how haptic interfaces can be optimized to enhance user experience.

Overview

This thesis is structured to provide a comprehensive examination of haptic interface design, beginning with an exploration of existing research and culminating in the development of a user-centered approach to haptic design informed by the proposed four-domain framework. The organization follows a logical progression, first establishing the foundational knowledge necessary to understand haptic interfaces, then analyzing the four haptic domains identified as a result of a structured literature review, and finally applying this framework to the discussion of haptic interface design. By maintaining this structure, the thesis ensures that each stage builds upon the previous one, providing a clear and systematic approach to understanding and improving haptic interaction.

In Chapter 2, I review and synthesize relevant literature on haptics across multiple academic disciplines to develop a structured framework that categorizes haptic interactions into four interdependent domains: the natural domain, governed by biological principles; the physical domain, governed by mechanical systems; the virtual domain, governed by computational models; and the artificial domain, governed by psychological and experiential factors. Each domain is examined in depth, detailing its role in haptic perception, feedback, and interface design. The chapter demonstrates how these domains interact, with each subsequent domain inheriting the limitations of the previous one while addressing its deficiencies. The result is a cohesive model that integrates biological, mechanical, computational, and psychological considerations into a unified framework of user-centered haptic design.

In Chapter 3, I apply the four-domain framework to develop a user-centered approach to haptic interface design. I identify three key criteria—adaptability, meaningfulness, and immersion—that are essential for improving haptic interactions by enhancing usability, intuitiveness, and engagement. I identify and discuss how to overcome critical challenges in haptic interface design and outline key design considerations from the HCI literature. I also distinguish between artifact design (i.e., the structuring of physical and mechanical components of haptic interfaces) and feedback design (i.e., the structuring of haptic signals and cues) to support effective interaction. By integrating these elements, this chapter moves beyond the theoretical foundation established in the literature review and into the practical considerations necessary for designing haptic interfaces that align with user needs.

In Chapter 4, I summarize the key contributions of this research and discuss its broader implications for haptic interface design. I emphasize how the four-domain framework and its application to user-centered haptic design can inform future developments in haptic technology. I also discuss practical implications of the framework and structured approach to user-centered haptic design for technology designers. Additionally, I outline the limitations of this research, particularly challenges that remain unresolved, such as the lack of a standardized haptic lexicon and the inherent difficulties of active exploration. Finally, I identify potential opportunities for future work, highlighting how the model and approach presented in this thesis can be leveraged to further refine haptic design methodologies and develop more immersive, discoverable, and meaningful haptic interactions.

Chapter 2

Literature Review: The Four Haptic Domains

The literature review[1] in this thesis serves as both a comprehensive synthesis of existing haptic research and the foundation for a structured framework that categorizes haptic interactions into four distinct, but interdependent domains. Rather than presenting a disconnected survey of past studies, this literature review is structured to develop a theoretical framework that can be systematically applied to the design of haptic interfaces. By examining haptic perception, feedback mechanisms, and interface development across multiple disciplines, this review constructs an organized model that integrates biological, mechanical, computational, and psychological considerations into a unified structure. This approach enables a more holistic understanding of haptic interaction, moving beyond isolated technical advancements to establish a framework that informs user-centered haptic design.

The methodology for this literature review follows a structured synthesis approach, which involves identifying, analyzing, and categorizing key studies that have shaped the field of haptics. The selection process prioritized peer-reviewed journal articles, conference proceedings, and foundational works that contribute to an understanding of haptic perception, feedback, and design principles. Sources were drawn from disciplines including human-computer interaction, cognitive science, robotics, virtual reality, and neuroscience to ensure a multidisciplinary perspective. The review process involved analyzing how different studies conceptualize haptic interaction, identifying recurring patterns in research findings, and classifying these findings within the four-domain framework. This structured synthesis differs from a traditional narrative review in that it

[1] This chapter includes excerpts from the author's undergraduate honors thesis: Gehman, N. (2024). *From haptics to haptic design.* Undergraduate honors thesis, Schreyer Honors College, The Pennsylvania State University, University Park, PA.

does not merely summarize existing research, but actively organizes it into a framework that serves as a theoretical model for haptic interface design.

Through this approach, I develop a four-domain framework of user-centered haptic design which serves as the foundation for this thesis. In the section on the natural domain, I explore biological and neurological principles underlying haptic perception, focusing on the somatosensory system and its role in interpreting tactile and kinesthetic feedback. In the section on the physical domain, I examine mechanical systems that translate haptic perception into tangible interface designs, such as force-feedback devices and vibrotactile actuators. In the section on the virtual domain, I investigate how digital and computational models simulate haptic interactions in virtual environments, addressing the role of algorithms and software in shaping tactile experiences. Finally, in the section on the artificial domain, I extend beyond technical considerations to explore the psychological and experiential factors influencing how users interpret and respond to haptic feedback. For each domain, I identify key principles, inherent limitations, and implications for haptic interface design, providing a structured perspective on the field.

Four-domain framework

Based on an in-depth review of literature on haptics across academic disciplines, I identify four haptic domains, explore them individually in detail, and explain how they collectively form a framework that supports theoretical development. The four domains of haptic design are the domain of the natural, the domain of the physical, the domain of the virtual, and the domain of the artificial. Each domain is governed by the foundational principles of a specific field: biology, physics, computer science, and psychology, respectively. Within each domain, only the laws of its guiding field are considered, and each domain contains a unique system that reveals a key consideration for haptic design. This key consideration represents everything a domain can tell us about haptic design. Moreover, each system has limitations which cannot be addressed within its domain, or any other domain. These can be thought of as design constraints. Likewise, each domain has a deficiency that can only be addressed in another domain. As a result, the deficiency of a domain can be thought of as the key consideration addressed by the next domain. Table 2-1 provides an overview of the four haptic domains in sequential order and starts to show how they build on each other.

Table **2-1**: Overview of the four haptic domains.

Characteristic	Domain of the natural	Domain of the physical	Domain of the virtual	Domain of the artificial
Field	Biology	Physics	Computer Science	Psychology
System(s)	Somatosensory	Mechanical	Computer	Cognitive
Deficiency	Quantification	Synthesization	Contextualization	None

The four haptic domains sequentially build on each other in two important ways. First, each domain inherits the limitations of the previous domain. Since limitations cannot be addressed, they restrict all aspects of haptic design and thus restrict all the key considerations. Because of this, the system limitations of one domain are imposed as external constraints (i.e., limitations based on the laws of a field outside the current domain) on the next domain. The second and most important way the domains build on each other is by addressing the deficiency of the previous domain. Unlike system limitations, domain deficiencies can be addressed through a system governed by different laws in a different domain. The system of the next domain can be thought of as the process by which the deficiency of the previous domain is addressed. In this way, the key haptic component outputted by this process can be thought of as the design considerations needed to address the previous deficiency. By inheriting the limitations and addressing the deficiencies of the previous domain, each subsequent domain moves closer to a complete set of haptic design principles.

There are a couple of things to keep in mind with the four domains. First, each domain and the system within it has limitations and deficiencies that when ignored often lead to failed haptic design. Second, the domains are interrelated, and failing to account for how they constrain each other often leads to failed haptic design. My framework not only provides a blueprint for how to succeed when designing haptic interfaces, but also reveals why some haptic interface designs fail.

In the sections that follow, I describe each domain, the field that governs it, and the external constraints placed on it. I break down each system into the process it uses, the components of the system, what the system takes in as input and produces as output, and the limitations of the system. I discuss how the key haptic component associated with the system encompasses all aspects of design for that domain, including considerations, limitations, approaches and affordances. The dimensions of each haptic domain are summarized in Table 2-2.

Table **2-2**: Dimensions of the four haptic domains.

Dimension	Haptic domain			
	Natural	Physical	Virtual	Artificial
System	Somatosensory system	Mechanical systems	Computer systems	Psychological system
Input	Active exploration	Haptic perception	Passive haptic feedback	Active haptic feedback
Process	Haptic sensation	Haptic stimulation	Haptic simulation	Haptic situation
Process type	Biological	Physical	Computational	Psychological
Output	Haptic perception	Passive haptic feedback	Active haptic feedback	Haptic cognition
Output type	Reactive	Static	Dynamic	Interpretive
Components	Tactile, proprioception	Transmissive, contact	Hardware, software	Emotion, environment, experience
Limitation addressed	Sensation	Quantification	Synthesization	Contextualization

Domain of the natural

The domain of the natural is governed by biology. This domain is the foundational haptic domain from which the other haptic domains build. The influential system of biology operating in this domain is the human somatosensory system, which is responsible for the process of haptic sensation. Haptic perception is the key haptic component in this domain. Exploring this foundational key haptic component yields insights and limitations essential in moving toward a theory of haptic design.

In this section, I synthesize findings from the literature to gain a deeper understanding of this domain and essential foundational knowledge by examining the somatosensory system, its constrains, components, limitations and results. Then, I discuss the deficiencies of this domain, which become especially relevant as we begin to consider other domains, particularly the next domain, the domain of the physical. I conclude the section by summarizing important takeaways from the domain of the natural that can inform a theory of haptic design.

Somatosensory system

The somatosensory system is the system of the natural domain. It is a biological system whereby a complex network of receptors and neural pathways reacts to environment signals (i.e., haptic sensations) as input and provides output in the form of haptic perception. The body's motor system is not just an output mechanism but a central feature of active exploration, which is unique to haptic perception compared to visual and auditory perception. The human body actively engages with its environment to perceive haptic stimuli. Unlike vision and hearing, haptic perception often requires active exploration—we must touch, press, or manipulate objects to fully understand them haptically (MacLean, 2000). This involves continuous feedback loops where actions inform perceptions, and perceptions guide further actions. In the rest of this section, I explore these processes in detail. Due to its foundational nature, the somatosensory system is not inherently constrained; however, I still propose some constraints that should be placed on this system from outside the domain of the natural. I also examine limitations within this system and take a closer look at its output, haptic perception. In Figure 2-1, I break down the specific aspects of the somatosensory system which are relevant to other haptic domains and principles of haptic design while also providing a more detailed understanding of the larger system at work.

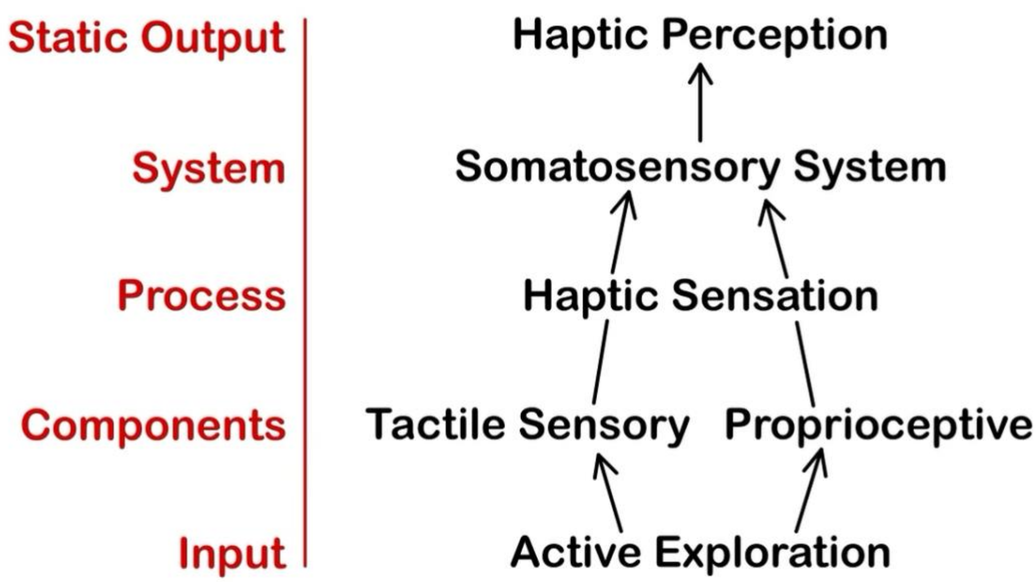

Figure **2-1**: Somatosensory system flowchart.

External constraints

As stated in the overview of the four haptic domains, each domain's system has constraints placed on it from outside the domain in which the system exists. This stems from the internal limitations of the system in the domain that precedes it. The first domain is the foundation upon which all the other domains build. However, constraining this first system's components to those with relevance to human-computer interaction (HCI) is beneficial. This prevents the exploration of components which are self-evidently incongruous with even the most basic principles of design.

Nociception is one such excludable component of the somatosensory system as it is responsible for the detection of pain (Dougherty, 2020). Any system that causes a user pain is one that is poorly designed (Norman, 2013). Any system in which designer wants to intentionally cause harm to a user is exceptional and an edge-case scenario, thus making it excludable from this thesis in pursuit of a general theory of design. Thermoception is the component of the somatosensory system that is responsible for detecting changes in temperature (Dougherty, 2020). The issue with thermoception comes from the extent to which our ability to design is constrained within this component. Humans' ability to detect minor changes in temperature is extremely poor; we are only able to consistently detect major changes in temperature. This alone reduces thermoception to an almost binary state of detection which leaves little room for design. To interact in this way, the hardware required to create a large change in temperature would be specialized, requiring more energy and restricting material options when compared with other equivalent modes of haptic interaction. The other components of the somatosensory system offer far better alternatives to nociception and thermoception. Later in this section, I explore these in depth. These alternatives are safer, more scalable, more variable, and offer a wider range of design choices.

Components of the somatosensory system

By breaking down the somatosensory system into its relevant components—tactile sensation and proprioception—we can develop a deeper understanding of how the somatosensory system detects various environmental signals as haptic sensations. The components of the somatosensory system (i.e., components of detection) are crucial and enable humans to create a model of haptic perception based on the haptic sensations detected. These components particularly demonstrate how can we perceive such a wide range of these signals as well as subtle changes within them. Each of these components plays a unique role in haptic perception, providing vital sensory input that helps us engage with both natural and artificially simulated environments. Components of the somatosensory system are summarized in Table 2-3.

Table **2-3**: Components of the somatosensory system.

Process: Haptic sensation	Somatosensory component	
	Tactile sensation	Proprioception
Input: Active exploration	Meissner's corpuscles Pacinian corpuscles Merkel discs Ruffini endings	Muscle spindles Golgi tendon organs Joint capsule receptors
Output: Haptic perception	Touch Pressure Vibration Texture	Body position Movement

Tactile sensation is concerned with the sense of touch, which allows for the perception of pressure, texture, and vibration (Dougherty, 2020). This component of the somatosensory system facilitates perception through four types of mechanoreceptors located in the skin: Meissner's corpuscles, Pacinian corpuscles, Merkel discs, and Ruffini endings. Each type of mechanoreceptor responds to different types of tactile sensation. Meissner's corpuscles are sensitive to light touch and light vibrations and are primarily located in areas of the skin that require high sensitivity, such as the fingertips and lips. Pacinian corpuscles detect deep pressure and deep vibrations; they are located deeper in the skin and are particularly important for perceiving fast, repetitive touches or vibrations. Merkel discs detect sustained pressure and fine texture; they provide detailed information about the surfaces we touch. These receptors are crucial for tasks that require precise touch, such as reading Braille or distinguishing between rough and smooth textures. Ruffini endings are sensitive to skin stretch and sustained pressure; they help the body perceive the direction of force applied to the skin, which is important for tasks that involve gripping or manipulating objects (Dougherty, 2020). Together, these mechanoreceptors make up the tactile sensory part of the somatosensory system and provide a foundational understanding of how humans can detect touch as it relates to pressure, texture, and vibration.

Proprioception refers to the body's ability to perceive its own position, movement, and balance in space (Proske & Gandevia, 2012). Unlike tactile sensation, which focuses on external stimuli, proprioception allows us to understand the internal states of our bodies. This component of the somatosensory system is primarily concerned with the awareness of body position and movement, even when we are not consciously observing it (Proske & Gandevia, 2012). There are three main types of proprioceptors: muscle spindles, Golgi tendon organs, and joint capsule receptors. Muscle spindles detect changes in muscle length and the rate at which a muscle is being stretched (Dougherty, 2020). This allows us to gauge how far and fast our muscles are extending, helping to control precise movements. Golgi tendon organs monitor muscle tension and prevent overexertion by sensing when a muscle is being stretched to its limit (Proske & Gandevia, 2012). This is important for preventing injury and maintaining muscle coordination. Joint capsule receptors are located in the joints and detect pressure and movement within the joints (Dougherty, 2020). They contribute to our sense of body positioning, especially in complex tasks like balancing or walking. Together, these proprioceptors make up the proprioceptive part of our somatosensory system and provide a foundational understanding of how we can detect motion and body orientation, as it relates to position and movement.

Internal limitations

One of the primary internal limitations of the somatosensory system is its biological range of perception. The somatosensory system can only process stimuli that fall within a certain threshold or range (Dougherty, 2020; Grunwald, 2008). For example, vibrations that are either too fast or too slow may fall outside the system's capacity to perceive them, meaning they cannot be converted into haptic sensations. Similarly, very small changes in pressure or texture might go undetected, especially if they do not sufficiently stimulate the tactile receptors in the skin (Jones & Lederman, 2006). These limitations are internal because they are inherent to the biological composition of the human body. As such, even though environmental stimuli may exist outside the threshold, the somatosensory system will fail to convert them into haptic sensations, and they will never be part of our haptic perception.

Based on the internal limitations of the biological somatosensory system, it would be a good design practice to ensure that the environmental stimuli generated by haptic systems fall within the perceivable range of the somatosensory system so that signals can be interpreted as haptic sensations, which results in haptic perception. If the signals generated by a system are outside this range, the user will not be able to detect them, making the interaction ineffective or imperceptible, meaning the signal will never result in haptic perception.

Domain limitations

The somatosensory system, while effective in perceiving stimuli within certain biological constraints, does not provide a mechanism to quantify haptic sensations or systematically understand haptic perceptions. For example, while we can detect a specific texture or pressure, our biological system does not provide a way to precisely measure or simulate that feeling in any universally standardized manner.

This limitation arises because the biological domain is not designed to quantify or replicate sensations—those are tasks better suited for the mechanical and virtual domains, which are discussed in later sections. The biological domain can only interpret and respond to stimuli in a subjective way, meaning that two people might perceive the same haptic sensation differently.

For design purposes, this limitation has significant implications. It means that replicating or simulating a specific haptic perception exactly as it is feels biologically may not be feasible, limiting our ability to fully reproduce haptic sensations across systems. Without a precise method of quantifying haptic perceptions, we also remain uncertain about the full range of what the somatosensory system can perceive. This in turn means that we cannot definitively know the extent to which these internal limitations affect higher-level domains.

Relevance to design

The somatosensory system is the foundational system within the domain of the natural, which provides a critical biological framework for understanding haptic perception. The limitations and constraints of this system have a direct impact on haptic design in the form of design limitations, design constrains, and design considerations. Understanding the range of perceivable environmental signals and the biological thresholds of the somatosensory system is essential for creating haptic interfaces that provide meaningful and detectable haptic interaction.

For haptic design, the most important takeaway is that all stimuli generated by haptic systems—whether they are touch-based (tactile) or motion-based (proprioceptive)—must fall within the perceivable range of the somatosensory system. This ensures that signals are processed and converted into haptic sensations, which then lead to haptic perception. By understanding the internal limitations of the somatosensory system, designers can avoid creating stimuli that fall outside this range, which would result in ineffective or imperceptible feedback for the user.

Finally, the domain limitations highlight that, while the somatosensory system is effective at interpreting environmental signals as haptic sensations, it does not offer a mechanism for quantifying these sensations. This means that any attempt to replicate or simulate haptic perceptions must occur in the higher-level domains once we have quantified and systematically reproduced these sensations. The inability to directly quantify haptic sensations also means that designers cannot precisely measure the full range of what users can perceive through the somatosensory system, making it necessary to rely on empirical data and user testing to fine-tune haptic feedback systems.

Summary

In summary, the somatosensory system's relevance to design lies in its ability to inform the design constraints for effective haptic interaction. Understanding biological constraints and thresholds ensures that haptic systems are aligned with haptic perception, while acknowledging the system's limitations helps guide the development of quantifiable and reproducible haptic feedback in future domains.

Domain of the physical

The domain of the physical builds on the domain of the natural and is governed by physics. It is responsible for quantifying haptic sensations as static properties of objects.

Mechanical systems are the primary systems in this domain, gathering haptic perceptions and translating them into tangible, physical interactions. This process enables the quantification of forces, resistances, and other physical stimuli. By turning haptic perceptions into measurable attributes, mechanical systems provide passive haptic feedback, which is static and unchanging based on a physical object's inherent properties.

In this section, I synthesize findings from the literature related to mechanical systems, which can be broken down into their transmissive and contact components. Then, I discuss the deficiencies of this domain, which are addressed by the next domain, the domain of the virtual. I conclude the section by summarizing important takeaways from the domain of the physical that can inform a theory of haptic design.

Mechanical systems

Processes in the physical domain occur through mechanical systems, which are systems of quantification. Mechanical systems inherit key haptic considerations of the natural domain and address associated deficiencies. Not only are they constrained by the somatosensory process in the natural domain, but they also have their own limitations. Mechanical systems take haptic perceptions as inputs, and, through a process of quantification, produce passive haptic feedback as outputs. In the rest of this section, I explore these processes in detail. First, I highlight some external constraints on this system that are inherited from the domain of the natural. Then, I explore two major components of mechanical systems and discuss how they transform haptic perception into haptic passive feedback. In Figure 2-2, I break down the specific aspects of mechanical systems which are relevant to other haptic domains and principles of haptic design while also providing a more detailed understanding of the larger system at work.

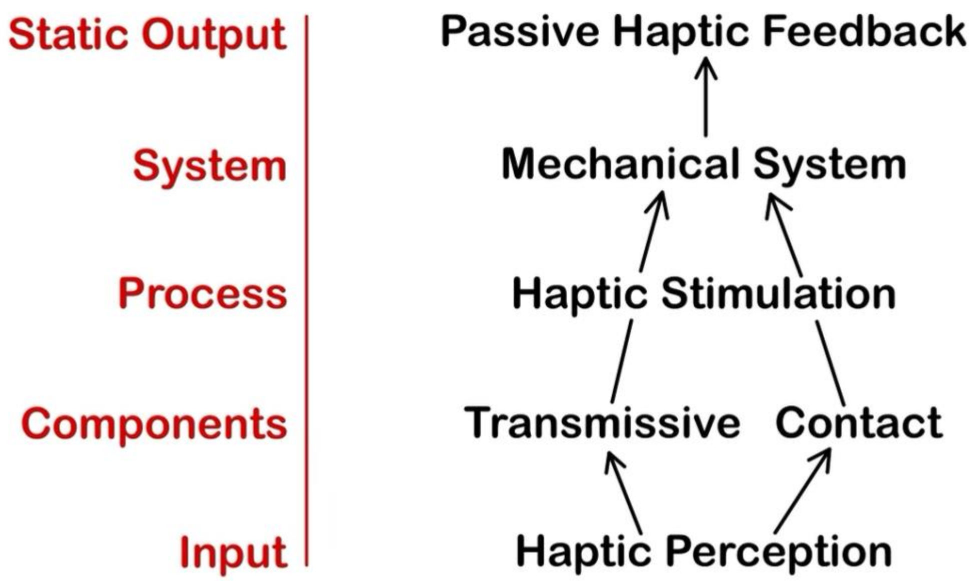

Figure **2-2**: Mechanical system flowchart.

External constraints

External constraints on the domain of the physical arise from the internal limitations of the somatosensory system in the domain of the natural. Since human biology can only perceive certain ranges of vibrations, pressure, or force, mechanical systems must focus on quantifying stimuli within these biologically perceivable ranges. For example, vibrations below 50 Hz or above 300 Hz are outside our biological perceptual range, meaning that stimuli within these ranges would not be perceived as haptic sensations (Jones & Lederman, 2006). Vibrations or pressures outside this range would go unnoticed by the somatosensory system, rendering their quantification irrelevant. This external constraint simplifies the design process for mechanical systems, as it limits the range of physical stimuli that must be quantified to only those that fall within the user's perceptual capabilities. Therefore, haptic design for mechanical systems must focus on producing physical feedback within these biological limits.

Components of mechanical systems

Mechanical systems can be broken down into their transmissive and contact components. Transmissive components—such as levers, gears, and springs—are responsible for transmitting motion and force (Colgate & Brown, 1994; Hayward & Maclean, 2007). Contact components—like surface textures or physical structures—create tactile sensations based on the interaction between the user and the mechanical object (Hayward & Maclean, 2007; Jones & Lederman, 2006; Lederman & Klatzky, 2009). For example, the chassis of a game controller provides the structure that houses mechanical feedback systems, allowing users to experience resistance or force when pressing a button or moving a joystick. Structural subcomponents include the frames and enclosures that provide the physical structure for mechanical devices. They hold all the working parts in place and guide the overall movement and force distribution. For instance, the chassis of a game controller holds the rest of the mechanical components in place. The structure of a mechanical system also enables us to take advantage of ergonomics, an important aspect of user affordance (Norman, 2013). Components of mechanical systems are summarized in Table 2-4.

Table **2-4**: Components of mechanical systems.

Process: Haptic stimulation	Mechanical system component	
	Transmissive	Contact
Input: Haptic perception	Levers Gears Actuators Pulleys Springs Dampers Motors Sensors	Structure Material
Output: Passive haptic feedback	Vibration Pressure Motion Resistance to motion Force Touch	Texture

Mechanical systems quantify haptic perception by taking an input from the user (e.g., pressing a button, moving a joystick) and, through transmissive and contact components, provide a passive form of haptic feedback. That is, passive haptic feedback is produced by the physical properties of objects in our environment. These physical properties of mechanical systems are quantifiable, and some are even synthesizable. Static passive feedback systems like springs and gears give consistent, unchanging feedback based on their structure. These systems are responsible for quantifying haptic perception, as mechanical systems make haptic stimuli measurable and replicable.

The system does not actively change based on conditions as a computer system might; instead, it provides feedback based on physical properties like resistance, force, or texture, all of which are mechanically controlled. Compared to a computer system that uses electrical, mechanical, and digital components (i.e., hardware and software) to synthesize active feedback, a mechanical system uses transmissive and contact components to deliver passive haptic feedback.

Through physics, various aspects of haptic perception are quantified, and as a result we can view them as physical properties of mechanical systems. Texture refers to the tactile sensation of surface characteristics, such as smoothness or roughness, or grip, which is quantified through friction (coefficient), and a physical property in the form of the material or structure of a mechanical system (Lederman & Klatzky, 1987). The tactile sensation of vibration is quantified through frequency (measured in Hertz, Hz), amplitude (meters), and duration (seconds), which are physical properties of motors, springs, and actuators in mechanical systems (Jones & Lederman, 2006). Pressure is a tactile sensation quantified by force per unit area (Pascal, Pa), and is a physical property of gears, levers, pulleys, and motors. Motion is a proprioceptive sensation measured by position (meters), velocity (meters per second), and acceleration (meters per second squared). In mechanical systems, components such as motors, actuators, and gears control motion. Resistance to motion is also a proprioceptive sensation quantified by torque (Newton meters), stiffness (Newtons per meter), and impedance (Ohms). Mechanical systems like dampers, springs, and levers embody these properties. Touch refers to the tactile sensation of interaction between the user and the mechanical system, quantified by force (Newtons) and displacement (meters) (Klatzky & Lederman, 1999; Lederman & Klatzky, 1987). Springs, switches, levers, pulleys, gears, and motors facilitate touch and have physical properties that are quantified like touch.

Table 2-5 details how mechanical systems quantify and translate haptic perception into physical properties resulting in passive haptic feedback. By linking each aspect of haptic perception to its corresponding physical property and mechanical embodiment, Table 2-5 provides a clear understanding of how haptic systems work in practice. Through these mechanical components, haptic interfaces replicate the tactile and motion-based sensations that users encounter in the physical world.

Table **2-5**: Quantification of our perceptions as physical properties.

Perception	Quantification	Physical properties
Texture	Friction (friction coefficient)	Material, structure
Vibration	Frequency (Hz), Amplitude (m), Duration (s)	Motors, actuators, springs
Pressure	Force per unit area (Pa)	Gears, levers, pulleys, motors
Motion	Position (m), Velocity (m/s), Acceleration (m/s2)	Motors, actuators, gears, pulleys
Resistance to motion	Torque (Nm), stiffness (N/m), impedance (Ohms)	Dampers, springs, levers
Touch	Force (N), displacement (m)	Springs, switches, levers, pulleys, gears, motors, sensors

Internal limitations

The domain of the physical builds on the domain of the natural, meaning the primary goal is to provide a system that addresses deficiencies of the field of biology. In addition to inheriting the limitations of the somatosensory system, mechanical systems have their own limitations. The output in this domain, passive haptic feedback, is tied to physical, unchanging properties, which limits a mechanical system's ability to encode dynamic information or respond flexibly to changing conditions. Once a mechanical system is engaged, its feedback is static and cannot dynamically alter it in response to the environment. For example, once a button is pressed, its mechanical resistance cannot change unless additional mechanisms are involved. As discussed in the next section, this stands in sharp contrast to virtual systems that allow for active and dynamic feedback.

Domain limitations

The domain of the physical is limited in its ability to adapt or dynamically alter its feedback, a deficiency that is addressed in the next domain—the domain of the virtual. While mechanical systems can provide accurate and reliable feedback, they lack the flexibility to simulate changes in the environment dynamically. This limitation highlights the need for higher-level computational systems to handle dynamic feedback, where forces and stimuli can be adjusted in real-time to better simulate physical interactions in a virtual context. Although mechanical systems enable us to quantify haptic stimulations and reflect them in the physical properties of an object, these properties cannot be changed, so their ability to encode information is extremely limited. As a result, this domain is deficient in its ability to dynamically change the properties of the device.

Relevance to design

The domain of the physical is essential to haptic design, as it provides a way to quantify physical properties and simulate static haptic sensations. This allows designers to integrate haptic feedback into devices where dynamic changes are not needed. For example, static interaction provides crucial information when using keyboards, steering wheels, or gaming controllers. Understanding the limits of what can be designed within the physical domain helps create more realistic, tangible, and predictable interfaces. Designers should note that mechanical systems are best suited for providing consistent feedback, but that the shift towards dynamic, real-time feedback needs to be handled by virtual systems, as this domain cannot respond to changing environmental factors. Moreover, mechanical systems are shaped by users' actions. A joystick, for instance, provides resistance as feedback, but only because the user moves it. In addition, the joystick has a limit or edge that is haptically perceived as resistance. The same applies to pulling a trigger on a game controller, mouse clicks, or keyboard presses—the system quantifies the input (user press) and translates that into physical feedback (tactile response).

While mechanical systems offer reliable, quantifiable haptic feedback, they are inherently limited in their dynamic capabilities, as the static nature of passive haptic feedback prevents mechanical systems from adapting to changing conditions. A key example is that a steering wheel in a car provides static feedback based on its physical structure —yet cannot dynamically change its texture or resistance as a digital system might. This presents a significant limitation in haptic design when designers need to encode dynamic or contextually shifting feedback into their systems.

Summary

The domain of the physical builds upon the domain of the natural by introducing quantification as a fundamental principle of haptic interaction. Governed by the laws of physics, this domain translates haptic perceptions into measurable, static properties, forming the foundation for passive haptic feedback. Mechanical systems are central to this process, utilizing transmissive and contact components to provide structured, repeatable haptic interactions. Transmissive components such as gears, levers, pulleys, and actuators enable motion and force transmission, while contact components like textures, surfaces, and structural materials create tangible tactile sensations. Through these mechanisms, mechanical systems define haptic properties such as texture, vibration, pressure, motion, resistance, and touch, making haptic feedback predictable and reliable but inherently static.

While mechanical systems provide quantifiable haptic feedback, they also inherit biological limitations from the somatosensory system in the domain of the natural. The perception of haptic stimuli is constrained by human sensory thresholds, meaning mechanical systems must operate within biologically perceivable ranges (e.g., vibrations between 50 Hz and 300 Hz). Additionally, mechanical systems lack the ability to dynamically alter their feedback once engaged. Unlike digital or computational systems, mechanical feedback is fixed, meaning it cannot adjust in real-time to changing environmental conditions. This limitation restricts its application in scenarios requiring adaptive or interactive feedback mechanisms.

Despite its static nature, the domain of the physical plays a crucial role in haptic design by offering a foundation for ergonomics, predictability, and structural affordances. Mechanical systems establish consistent interactions, such as the tactile resistance of a keyboard key or the structured motion of a joystick. These interactions form the basis for user expectations in haptic interfaces, ensuring that feedback remains intuitive and discoverable. However, as the demand for more immersive, responsive, and adaptive haptic experiences grows, the limitations of mechanical systems become more apparent.

To overcome these limitations, the domain of the virtual introduces a new paradigm: the ability to synthesize dynamic haptic feedback using computational systems. While the physical domain excels in static haptic interactions, the virtual domain expands haptic design by enabling active feedback, dynamically simulating forces, vibrations, and resistances based on real-time inputs. The next section explores how computational systems address the deficiency of passive haptic feedback by introducing programmable, adaptive haptic responses, paving the way for more immersive and interactive haptic experiences.

Domain of the virtual

The third domain—the domain of the virtual—focuses on the digital aspects of haptics. This domain builds on the physical domain, and by extension, the natural domain. The domain of the virtual is governed by computer science and is responsible for transforming passive haptic feedback (inputs) into active haptic feedback (outputs). Active haptic feedback thus is the key haptic component derived from this domain. In the domain of the virtual, computer systems take in a continuous stream of information as input and synthesize haptic feedback to simulate physical sensations. In contrast to the static, passive haptic feedback provided by mechanical systems in the domain of the physical, virtual systems can dynamically generate active haptic feedback by adjusting forces, vibrations, and sensations in real time. The systems in this domain simulate the experience of interacting with physical objects in a digital environment, often integrating feedback to create immersive virtual experiences.

In the rest of this section, I synthesize insights from the literature to provide a deeper understanding of this domain by exploring the constraints, components, and limitations of computer systems as they relate to haptic design. Then, I discuss deficiencies of this domain as a whole and key design considerations related to the domain of the virtual that can inform a theory of haptic design.

Computer systems

Computer systems take passive haptic feedback from the physical world (e.g., pressing a physical button) and convert it into digital signals that can be manipulated and simulated dynamically (Srinivasan & Basdogan, 1997). The primary output of this system is active haptic feedback, where the computer controls how the feedback changes based on user input and environmental conditions (MacLean, 2000). The system dynamically adjusts haptic stimuli (e.g., changes in force or texture) based on programmed parameters, such as by increasing resistance in a virtual steering wheel to simulate driving on a rough surface. Likewise, smartphones have digital keyboards which provide vibrotactile feedback to simulate the feedback of springs in mechanical keyboards. In the rest of this section, I explore these processes in detail. First, I highlight some external constraints on this system that are inherited from the domain of the physical. Then, I explore two major components of computer systems and discuss how they transform passive haptic feedback into active haptic feedback. Figure 2-3 breaks down the specific aspects of computer systems which are relevant to other haptic domains and principles of haptic design, while also providing a more detailed understanding of the larger system at work.

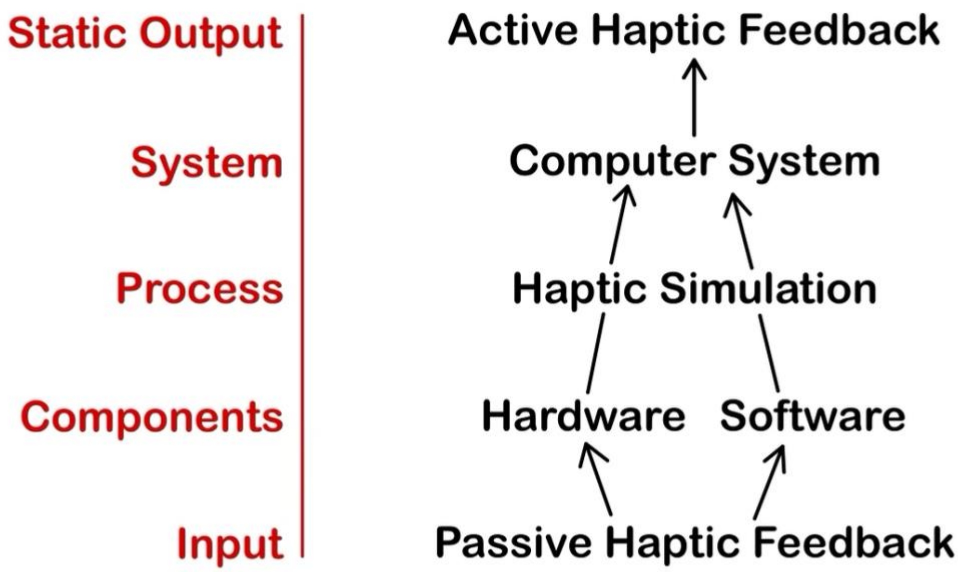

Figure **2-3**: Computer system flowchart.

External constraints

The external constraints of the virtual domain are inherited from the physical domain's mechanical systems—specifically, the limitations of passive haptic feedback. Since mechanical systems can only provide static feedback, virtual systems must dynamically simulate sensations to make up for this limitation. These constraints also stem from the biological limitations inherited from the domain of the natural, meaning that simulated feedback must remain within the perceptible range of human senses (e.g., vibration frequencies that the skin can detect). For example, a virtual system simulating the texture of a surface must account for the fact that human skin can only detect a certain range of vibration frequencies. A virtual system would be ineffective if it generated vibrations outside this range since they would not be perceptible to the user. As a result, virtual systems are constrained by both the biological limits of the somatosensory system and the physical limits of the mechanical systems that interact with the real world.

Components of computer systems

As shown in Figure 2-3, computer systems for haptics include both hardware (sensors, actuators) and software components that allow for the continuous adjustment of haptic stimuli. Software synthesizes haptic interactions and ensures real-time responsiveness (Biggs & Srinivasan, 2002). This is essential for applications like virtual reality (VR), where the user's movements and actions need to be simulated and mirrored through dynamic feedback in real time to create a more immersive experience.

Hardware is used to gather inputs and produce outputs. Sensors gather data from the user's interaction with physical or virtual objects (e.g., motion sensors, gyroscopes, accelerometers), and actuators and motors deliver synthesized feedback to the user (e.g., vibrating controllers, force feedback systems). Software components are responsible for transforming inputs into outputs in the virtual domain. Digital signal processing (DSP) systems convert analog input into digital data, and vice versa, allowing for the real-time adjustment of haptic signals, and algorithms to simulate and adjust haptic stimuli in real time (Maclean & Hayward, 2008). These software components enable the dynamic control of feedback and allow for programmable haptic responses.

These components work together to simulate dynamic haptic sensations that respond to the user's input in real time. By integrating hardware and software components, computer systems can control the intensity, frequency, and duration of haptic feedback with precision, allowing for a more immersive experience in applications like VR, gaming, and robotic surgery. Components of computer systems are summarized in Table 2-6.

Table **2-6**: Components of computer systems.

Process: Haptic simulation	Computer system component	
	Hardware	Software
Input: Passive haptic feedback	Actuators Motors Sensors	Digital signal processing (DSP) Algorithms
Output: Active haptic feedback	Dynamic vibration Dynamic pressure Dynamic motion Dynamic resistance to motion Dynamic force Dynamic touch	

Internal limitations

The internal limitations of the virtual domain arise from the inherent constraints of computational systems. While virtual systems can dynamically synthesize haptic feedback, they are limited by the precision and accuracy of the hardware and software components. For instance, while a virtual system may attempt to simulate the feel of a soft object, the precision with which this sensation is generated depends on the quality of the actuators, sensors, and the algorithms governing them. Additionally, computational systems cannot fully replicate the richness of haptic sensations due to the current limitations in simulating complex physical interactions, such as soft tissue deformation in virtual surgery or the subtle texture of a fabric in a virtual shopping environment.

Computer systems also are limited by what they can synthesize. Some sensations are difficult to simulate, such as texture (Hayward & Maclean, 2007; Klatzky et al., 1987). Hardware limitations also come into play in the domain of the virtual. For example, humans can accurately perceive vibrations up to 300 Hz (Jones & Lederman, 2006), but if an actuator can only produce 200 Hz, the system's ability to simulate severe vibration is limited. Limitations also can stem from the physical structure of a device. For example, a smartphone is small, so it is impossible to embed a large motor in it.

Another internal limitation is the latency between user input and the system's response. Delays in processing and delivering feedback can break immersion and reduce the effectiveness of the feedback (MacLean, 2000). As a result, designing haptic feedback systems for virtual environments requires careful consideration of processing speed, hardware capabilities, and real-time feedback.

Domain limitations

While the domain of the virtual allows for active haptic feedback, it is still limited by the fact that all sensations must be simulated, not physically replicated. The complexity of real-world touch is difficult to mimic precisely, and the sensations generated by virtual systems can sometimes feel artificial or limited in scope. For example, while a virtual system may be able to simulate the feel of a rough surface, it cannot yet fully replicate the feel of running your fingers over different types of textured fabrics with high fidelity (Hayward & Maclean, 2007; Klatzky et al., 1987). Additionally, virtual systems cannot reproduce feedback involving highly complex interactions, such as the subtle changes in resistance felt during fine motor control (e.g., performing a delicate task with a virtual tool) (Okamura, 2004). For example, if the range of perceivable sensation has been quantified as 50–300, but a motor's range is 0–200, the effective range is 50–200. However, it is difficult to decide what level of output to provide without knowing how users are going to interpret and react to the different haptic stimulation we can simulate. To do so, we need to understand haptic cognition, which is addressed by the next domain.

Relevance to design

The domain of the virtual is essential for dynamic haptic design, allowing designers to create experiences where haptic feedback adjusts based on user input and environmental conditions. This is crucial in applications where interaction with virtual objects needs to feel realistic and responsive, such as in VR environments, gaming, and remote surgery.

From a design perspective, the virtual domain offers opportunities to simulate environments and interactions that are difficult or impossible to replicate in the real world. However, designers must be aware of the limitations of current computational systems and work within those constraints to create meaningful, immersive experiences. Careful attention must be paid to latency, precision, and user perception to ensure that the feedback feels natural and contributes to a coherent interaction experience.

Summary

In summary, the domain of the virtual provides the tools necessary for synthesizing active haptic feedback, but is constrained by the limitations of current technology and the complexity of real-world touch interactions. By addressing these challenges and understanding the limits of virtual systems, designers can create more effective and immersive haptic interfaces that respond in real time to user input.

Domain of the artificial

The domain of the artificial is governed by the field of psychology, focusing on how humans interpret, contextualize, and react to haptic feedback. It is the final domain, bringing together inputs from natural, physical, and virtual domains and translating them into meaningful experiences and actions. The key haptic component in this domain is haptic cognition—the user's cognitive and emotional response to haptic feedback and how they contextualize it.

In *The Sciences of the Artificial*, Herbert Simon (1996) argues that artificial systems are designed to serve human needs and are shaped by cognitive constraints, environmental contexts, and learned behaviors. This perspective aligns closely with the domain of the artificial in haptic design, where the user's cognitive and emotional response to haptic stimuli determines how feedback is processed and understood. Unlike the natural, physical, and virtual domains, which deal with biological perception, mechanical feedback, and digital synthesis, respectively, the artificial domain is concerned with how humans interpret and assign meaning to haptic sensations.

Simon's framework suggests that artificial systems function as intermediaries between human cognition and the external world, helping users translate sensory input into actionable knowledge. In haptics, this translation process occurs when users contextualize haptic feedback within their broader experiences, expectations, and emotional states. For example, the same vibrational cue can be perceived as a warning in a driving scenario but as a confirmation in a mobile interface. This underscores the importance of designing haptic feedback that aligns with cognitive affordances, ensuring that users intuitively grasp its intended function.

In this domain, the psychological system processes haptic feedback and situates it within the user's emotional state, environment, and experiences. This domain addresses the deficiency of the virtual domain by filling gaps in active haptic feedback with the user's psychological interpretation of the stimuli. The domain of the artificial is essential for understanding how users make sense of and interact with haptic systems, giving designers insight into how feedback should be structured to align with human cognition and emotional reactions.

Psychological system

In the domain of the artificial, the psychological system takes the haptic feedback generated in the physical and virtual domains and situates it within the user's broader cognitive framework. The result of this process is haptic cognition, where the user's interpretation of the feedback informs how they react and engage with the interface. Haptic cognition is the ability to contextualize various haptic stimulations into a broader haptic situation. It is how users make sense of the things they haptically perceive as they actively explore the surrounding environment. Haptic cognition takes what users are feeling and gives it meaning by situating it within their broader understanding. Haptic cognition is important because it can help designers understand how a user is likely to react and or interpret a given haptic situation. Once we understand haptic cognition, we can take a user-centered and informed approach to haptic design that considers all four domains.

In the rest of this section, I explore these processes in detail. First, I highlight some external constraints on the psychological system that are inherited from the domain of the virtual. Then, I explore the major components of the psychological system and discuss how they transform active haptic feedback into haptic cognition. Figure 2-4 breaks down the specific aspects of the psychological system which are relevant to other haptic domains and principles of haptic design while also providing a more detailed understanding of how the larger system functions.

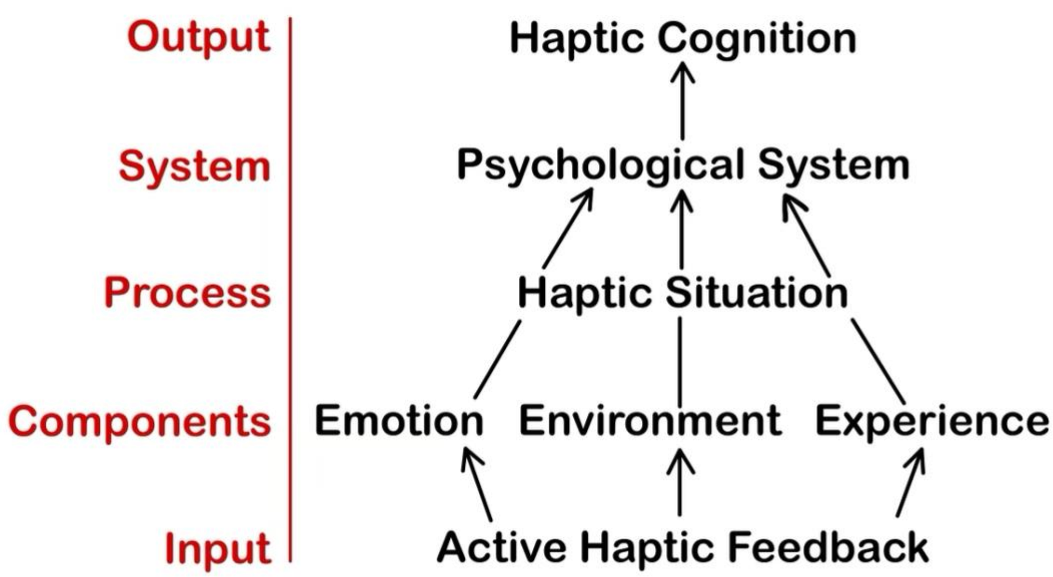

Figure **2-4**: Psychological system flowchart.

External constraints

External constraints in the domain of the artificial are inherited from the limitations of the domain of the virtual. Since the virtual domain cannot replicate every detail of real-world touch or dynamically adjust stimuli in all contexts, the domain of the artificial must compensate by relying on the user's cognitive processing. The virtual domain's inability to fully simulate real-world sensations places a cognitive burden on users, who must mentally "fill in" the gaps to make sense of the feedback. This limitation means that designers must create haptic systems that are not only perceptually effective but also intuitively interpretable, taking into account users' cognitive limitations and expectations.

Components of the psychological system

The central focus of the psychological system is not just the perception of haptic feedback, but associated interpretation and decision-making processes. The psychological system has three main components: emotion, environment, and experience. These components ensure that haptic feedback does not exist in isolation, but is interpreted within a broader cognitive and emotional framework. For example, haptic feedback about the amount of force being used in a virtual surgery simulation is likely to be interpreted differently by a trained surgeon than by a novice, as the experienced surgeon has a greater cognitive understanding of how the tool should feel during certain procedures.

The user's emotional state and environmental factors shape their reactions to haptic stimuli. For example, vibrations during a VR experience might feel alarming in a horror game, but calming in a meditation app, even if the physical stimuli are nearly identical. Similarly, a driver may interpret a vibrating steering wheel differently depending on whether they are driving in heavy traffic or on an open road.

Users' previous experiences interacting with similar systems or interfaces also shape how they interpret new feedback. Their understanding of how haptic systems work or familiarity with specific haptic patterns (e.g., learning the meaning of vibrations in a game) influence how active feedback is interpreted. These mental models of haptic interfaces influence haptic cognition, which in turn plays a role in affordances. For example, users have a mental model for keys and buttons, so even if they have not seen a specific haptic interface before, they can infer the parts of it that align with other haptic interfaces they have seen in the past. Likewise, when using a haptic-enabled steering wheel that vibrates to warn of lane departure, the user's cognition translates the vibration into an understanding that they need to correct the car's trajectory.

Users' experiences also contribute to a shared haptic grammar. Our haptic grammar heavily impacts our ability to communicate through haptic interfaces, and more specifically our ability to encode information through the simulation of physical properties as active haptic feedback. While it has been argued that our haptic grammar is not as well defined as our graphic or auditory grammars (MacLean, 2000), I believe that is no longer the case. Our shared haptic grammar develops as we interact with the world around us and ascribe meaning and emotions to various haptic inputs. In recent years, users have been interacting with technology and responding to haptic stimuli at an unprecedented rate. Thus, I contend that our haptic grammar is now defined well enough to be able develop a theory of haptic design. Components of the psychological system are summarized in Table 2-7.

Table **2-7**: Components of the psychological system.

Process: Haptic situation	Psychological system component		
	Emotion	Environment	Experiences
Input: Active haptic feedback	Feelings	Contextual factors	Mental models, Grammar
Output: Haptic cognition	Interpretation of vibration Interpretation of pressure Interpretation of motion Interpretation of resistance to motion Interpretation of force Interpretation of touch		

Internal limitations

Internal limitations of this domain arise from variability in human cognition and emotional responses. Since different users have different levels of experience, knowledge, and emotional reactions, there is no universal standard for how haptic feedback will be interpreted. A haptic cue that feels intuitive to one user might be confusing or unintelligible to another. This variability places a limitation on the design of haptic systems, as designers cannot predict with certainty how each user will interpret feedback. A major constraint here is our grammar, as we can best communicate based on what is already understood and has been ascribed meaning. Cognitive overload is another significant limitation. If a user is presented with too much haptic feedback, or feedback that is too complex, they may become overwhelmed and unable to effectively process the sensations. This can lead to confusion, errors, or even discomfort, reducing the overall effectiveness of the system.

Domain limitations

While the domain of the artificial can support the contextualization and interpretation of haptic feedback, it has limitations. The primary limitation is that cognition alone cannot compensate for poorly designed haptic feedback. If the feedback is too subtle, confusing, or inconsistent, no amount of cognitive interpretation will make it effective. Additionally, since the domain of the artificial relies on users' prior experiences and knowledge, it is limited in its ability to provide effective feedback to users who are unfamiliar with the system or context.

The deficiency of this domain is that it relies heavily on the user's psychological state and prior knowledge to fill in the gaps left by physical and virtual feedback systems. This means that if physical or virtual feedback is poorly designed, psychological systems will not always be able to compensate, leading to a dissonant or disconnected experience.

Relevance to design

The domain of the artificial is crucial for designing intuitive and contextually appropriate haptic feedback. Designers must understand how users interpret feedback based on their emotional state, the environment, and their prior experiences. This domain highlights the importance of creating feedback that aligns with user expectations and can be easily contextualized.

Taking into account the limitations of user cognition, designers can avoid creating haptic interfaces that are overly complex or confusing. Instead, they can focus on designing feedback that is simple, intuitive, and effective, providing users with clear and actionable cues that align with their mental models and cognitive capabilities. This approach leads to more engaging and immersive experiences, where users feel connected to the haptic feedback and can easily interpret its meaning. It is here where we become concerned with user-centered haptic design.

Summary

The domain of the artificial serves as the final stage in haptic design, integrating insights from the natural, physical, and virtual domains to shape how users interpret and respond to haptic feedback. Governed by psychology, this domain introduces haptic cognition, the process through which users assign meaning to haptic stimuli based on emotion, environment, and experience. Unlike previous domains, which focus on perception, quantification, and synthesis, this domain contextualizes feedback, allowing users to interpret haptic signals intuitively.

Since virtual systems cannot fully replicate real-world touch, users must mentally fill in gaps, relying on prior knowledge and cognitive models to make sense of feedback. This places constraints on haptic design, requiring feedback to be intuitive, consistent, and aligned with user expectations. Emotional and situational factors further shape interpretation—identical vibrations may signal urgency in one context (e.g., an alert) but reassurance in another (e.g., relaxation).

A major challenge of this domain is cognitive variability—different users may interpret the same haptic signal differently, leading to inconsistencies in user experience. Despite these limitations, this domain highlights the importance of designing haptic feedback that is discoverable, interpretable, and meaningful.

With haptic cognition established, we can now explore a user-centered framework for haptic design, synthesizing key insights across all four domains to create interfaces that are not only perceptible and responsive but also intuitive and contextually meaningful.

User-centered design principles

A user-centered theory of haptic design must be grounded in user-centered design principles. First, as Norman (2013) suggests, effective design makes affordances clear. Users should be able to feel their way through a haptic interface without needing visual or textual guidance. Moreover, haptic feedback should provide clear cues about its functionality. For instance, when a user presses a virtual button that simulates a click, the feedback should be intuitive and unmistakable, indicating to the user that an action has been successfully initiated. Feedback plays a crucial role in informing the user that an action has been registered. Norman's principle of feedback applies strongly to haptic systems, as users need immediate and understandable signals to ensure their actions are recognized. Vibrations, resistance, or other tactile signals should be responsive and consistent across devices and systems to avoid user confusion. For example, a vibrating alert on a phone should be perceived similarly across different apps and interactions. This consistency reduces cognitive load and helps users form reliable mental models of interaction. Haptic designs also should prioritize simplification, and designers should avoid adding unnecessary complexity. In addition, Norman's visibility principle emphasizes that users should understand how to interact with the system without requiring additional explanation. Likewise, discoverability is an important user-centered design principle. Unlike visual and auditory feedback, which users can perceive passively, haptics require active exploration. Designers need to ensure that the haptic affordances in their interfaces are easily discoverable through active exploration. The design should encourage users to engage with the interface haptically, such as by providing subtle vibrational feedback when fingers approach certain areas of a touchscreen.

Haptic design must also account for common ground, a concept Norman (2007) discusses extensively in The Design of Future Things. In traditional interfaces, common ground refers to the shared understanding between humans and systems that enables smooth interaction. In haptics, this principle is crucial—users should immediately recognize and understand the function of haptic feedback based on their prior experiences. For instance, when a car's steering wheel provides haptic feedback by vibrating to indicate lane departure, this signal should be consistent with existing conventions so the user instinctively knows how to respond. If the system introduces new, unfamiliar haptic signals, users may not correctly interpret them, reducing effectiveness. Establishing common ground ensures that haptic feedback is not alien or confusing, but instead fits within a user's existing cognitive framework for interpreting tactile information.

Additionally, Norman's (2004) concept of emotional design plays a significant role in user-centered haptics. Haptic feedback is not just functional—it has the power to evoke emotions. When designed thoughtfully, haptic interactions can enhance user engagement, trust, and satisfaction. For example, the soft haptic pulse of a meditation app can convey relaxation, while the sharp vibration of a game controller in response to damage can heighten urgency and immersion. Users are not passive recipients of haptic stimuli; they emotionally respond to the tactile cues they experience. Emotional design reminds us that haptics should not merely be informative but should also evoke appropriate emotions that align with the user's goals and expectations.

By integrating discoverability, common ground, and emotional design, haptic interfaces can move beyond mere functional feedback to create intuitive, meaningful, and engaging user experiences. A user-centered haptic design must not only ensure that interactions are perceptible and interpretable but also align with the user's cognitive, experiential, and emotional context. These principles lay the groundwork for the structured, user-centered approach to haptic design developed in this thesis.

Summary

My review and synthesis of the literature on haptics has surfaced several insights that could inform a theory of haptic design which thus far has remained elusive. In the domain of the natural, it is possible to identify that we should further constrain our range of haptic perception to that which is safe for humans. Even though users may be able to perceive something violent, a haptic interface should not harm them. Moreover, the biological limitations of the somatosensory system provide the fundamental constraints on what can be felt or perceived, particularly in terms of range, sensitivity, and motor responses. While these limitations shape design, they also offer insights into how to design within human sensory capabilities.

In the domain of the physical, we can apply principles of ergonomics and affordances to make interfaces more enjoyable to use and easier to figure out. For example, buttons clearly afford pressing, and joysticks afford moving; likewise, it is clear how a mouse or Xbox controller fits in a user's hand and does so comfortably. In this domain, the mechanical systems that quantify haptic perceptions are restricted by the immutable properties of physical objects. Passive haptic feedback is static and is limited by materials and mechanical components, but it offers reliable feedback when designed well.

In the domain of the virtual, computer systems offer affordances to designs, as haptic feedback can signify different meanings to users. In this domain, the power of computer systems allows the real-time simulation of active haptic feedback that is dynamic and customizable, offering designers more flexibility to adapt to different situations. This flexibility, however, introduces challenges in creating understandable and intuitive feedback.

Finally, in the domain of the artificial, once we know how users interpret haptic situations, we can better communicate and encode information. The overall goal of design (specifically user-centered design) is to help users achieve their goals. Well-designed systems can help users achieve any goal they may have in any given situation and in any given environment. In this domain, the psychological system governs how users contextualize and interpret haptic feedback. While designers cannot fully predict users' reactions, understanding the cognitive processing of haptics can guide the development of intuitive and meaningful feedback loops.

A user-centered theory of haptic design also must be grounded in user-centered design principles. Effective design makes affordances clear. Users should be able to feel their way through a haptic interface without needing visual or textual guidance. Moreover, haptic feedback should provide clear, consistent cues about its functionality. Haptic designs also should prioritize simplification; users should understand how to interact with the system without requiring additional explanation. Likewise, designers need to ensure that the haptic affordances in their interfaces are easily discoverable through active exploration.

Synthesizing the insights from my literature review and principles of user-centered design, I propose a framework that could provide the foundation for a user-centered theory of haptic design (see Figure 2-5). This foundational framework for a user-centered theory of haptic design is based on my analysis of four haptic domains: the domain of the natural, the domain of the physical, the domain of the virtual, and the domain of the artificial. Each domain encapsulates a critical field—biology, physics, computer science, and psychology, respectively—offering unique insights and constraints essential to a user-centered theory of haptic design. By examining each domain's systems, processes, and limitations, I have identified a key consideration for haptic design revealed by each domain—haptic perception, passive haptic feedback, active haptic feedback, and haptic cognition—which when combined create a structured approach for designing effective and immersive haptic interfaces. In the domain of the natural, the somatosensory system shapes haptic perception. In the domain of the physical, mechanical systems quantify haptic perception as passive haptic feedback. In the domain of the virtual, computer systems synthesize these interactions, dynamically simulating haptic responses as active haptic feedback. Finally, in the domain of the artificial, user experience is contextualized by psychological systems, fostering cognitive interpretation and situational adaptation.

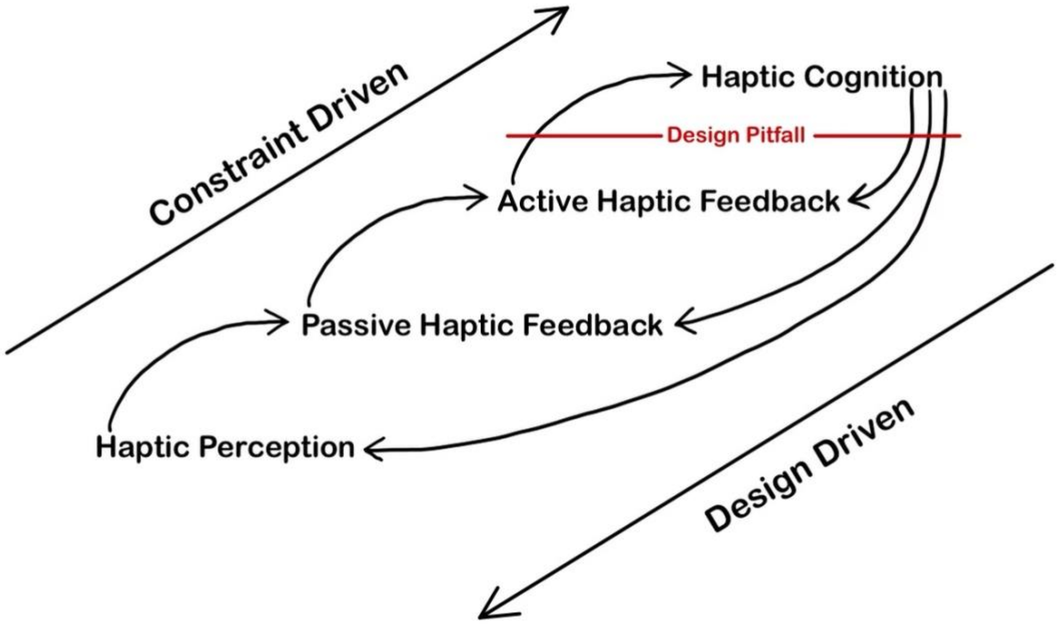

Figure **2-5**: Framework for a user-centered theory of haptic design.

By identifying the distinct, yet interdependent roles each domain plays, this framework provides the foundation for a novel, user-centered approach to haptic interface design. In Chapter 3, I apply the framework developed in this chapter and combine it with the principles of affordance, feedback, and immersion to develop an approach could support meaningful and accessible haptic experiences across a range of applications.

Chapter 3

Discussion: Designing User-Centered Haptic Interfaces

The theoretical framework developed in Chapter 2 provides a structured understanding of haptic design by identifying four key domains: the domain of the natural, the domain of the physical, the domain of the virtual, and the domain of the artificial. While these domains offer a way to conceptualize haptic systems and their limitations, they do not inherently provide actionable steps for designing more effective and user-centered haptic interfaces. In this chapter, I apply insights from the four domains to develop a user-centered approach to haptic design by addressing critical challenges that hinder the progression of haptic interfaces. These challenges include variability in haptic perception, low discoverability of haptic features, the active nature of haptic exploration, the lack of a haptic lexicon, and low replicability and fidelity of haptic feedback. By analyzing these challenges, it is possible to identify design principles that contribute to a more effective and standardized approach to haptic interface design.

The four-domain framework provides a structured understanding of haptic systems, but designing effective interfaces also requires applying user-centered design principles to overcome real-world challenges. In the second section, I discuss how to leverage the framework's insights along with key HCI theories to address critical issues that hinder haptic interface usability. I identify major challenges in haptic design and propose strategies grounded in user-centered principles to improve adaptability, meaningfulness, and immersion of haptic feedback.

In the third and fourth sections, I integrate broader design principles from various sources, including Norman's (2013) design guidelines and multimodal interaction theory (Oviatt, 2007) to ensure these solutions align with how users perceive and use technology. In doing so, I differentiate between the design of the physical artifact (the device itself) and the feedback it produces, highlighting how each aspect can be optimized by applying the proposed framework.

Key challenges in haptic design and proposed strategies

Several recurring challenges must be addressed to make haptic interfaces more user-friendly. Below, I summarize the key challenges and outline strategies to address them informed by the four-domain framework and prior research.

Variability in haptic perception

A major challenge in haptic design is the inherent variability in human haptic perception. Unlike visual or auditory stimuli, which can be standardized with relative ease (e.g., font size adjustments or volume controls), haptic perception is highly individualized, influenced by factors such as age, skin condition, prior exposure to tactile stimuli, and even physiological differences (Lederman & Klatzky, 2009). For instance, individuals with calloused hands, such as musicians or manual laborers, may have reduced sensitivity to fine tactile details, whereas others may have heightened sensitivity. This variability complicates the development of universal haptic interfaces, as the same feedback may be perceived differently by different users.

One potential solution is to develop adaptive haptic systems that calibrate feedback based on user sensitivity. Similar to how display brightness can adjust to ambient lighting conditions, haptic intensity could be personalized through machine learning models that analyze user responses over time. Recent research in adaptive haptic interfaces has explored how force feedback can be adjusted in real-time based on user interaction patterns (Bau et al., 2010). Providing user settings for haptic intensity, or auto-calibrating on first use (as seen in some game controllers), can accommodate a broader range of users. Implementing such personalization in commercial devices, however, remains challenging due to hardware constraints and the lack of a standardized framework for user calibration. Addressing these issues requires a deeper understanding of how user-centered design principles can be applied to create adaptable and accessible haptic experiences.

Low discoverability

Haptic feedback also suffers from an inherent discoverability problem due to its invisible nature. Unlike visual or auditory cues, which are passively perceived, haptic feedback requires active engagement, making it difficult for users to intuitively recognize and explore haptic features within an interface (Norman, 2013). Haptic features are often “invisible;” unlike a button or icon, tactile feedback does not announce itself visually. Thus, users might not realize an interface element has haptic feedback, leading to underuse or confusion. This limitation is particularly evident in touchscreen devices, where the absence of physical affordances makes it challenging to design haptic elements that users can easily locate and interpret.

A possible strategy to improve discoverability is the use of multimodal feedback. Combining haptics with visual or auditory cues can help guide users towards haptic interactions (Klatzky & Lederman, 1999). For example, when a user hovers over an interactive element on a touchscreen, a subtle vibration could be paired with a visual highlight, reinforcing the affordance of that element. Additionally, guided onboarding experiences that explicitly introduce users to haptic features through interactive tutorials, can enhance familiarity and engagement. Prior studies suggest that users who receive guided exposure to haptic features are more likely to discover and utilize them effectively in subsequent interactions (MacLean, 2000). In short, designers should signal the presence of haptic feedback through other channels until users become familiar with them. These strategies highlight the need for intentional and user-friendly haptic designs that align with the principles of affordance and discoverability.

Active nature of haptic exploration

Unlike vision and hearing, which can be perceived passively, haptic perception is inherently active—it requires movement and intentional interaction with the environment (Gibson, 1962). This characteristic poses a fundamental design challenge, as users must engage physically with an interface to perceive its haptic feedback. This requirement makes haptic feedback more cognitively demanding than visual or auditory feedback, as it involves both sensory processing and motor control.

One way to address this challenge is through designs that encourage natural and intuitive exploration. For instance, haptic feedback can be incorporated into gestures that users already perform, such as pressing, swiping, or gripping. For example, adding haptic confirmation to a normal button press or vibration during a swipe gesture makes the feedback feel like a natural extension of the action. Research on gesture-based haptics has shown that users are more likely to engage with haptic interfaces when feedback is seamlessly integrated into familiar interactions (Hayward & MacLean, 2007). Furthermore, incorporating predictive feedback—where the system anticipates user actions and provides subtle cues—can make haptic exploration feel more natural and responsive (Biggs & Srinivasan, 2002). Prior studies indicate that when haptic responses are seamlessly woven into familiar interactions, users find the experience more intuitive and engaging. By designing interfaces that align with natural motor behaviors, designers can reduce the cognitive burden of active haptic exploration and improve user engagement.

Lack of a haptic lexicon (standard meaning)

One of the most significant barriers to effective haptic design is the lack of a well-defined haptic lexicon. While visual and auditory interfaces have well-established conventions (e.g., color-coding systems, musical notations, and iconography), haptic feedback lacks a standardized grammar for encoding and communicating information (MacLean, 2000), making it difficult to create consistent and universally recognizable haptic signals. Johnson-Laird (1983) proposed that standardized representations improve usability, a principle that applies equally to haptic feedback. By establishing a common haptic lexicon, designers can create more predictable and intuitive interactions across devices. For instance, a universal vibration pattern for error states could help users develop cross-platform familiarity, just as the “red X” universally signifies an error in graphical interfaces.

While some researchers have argued that the limited haptic lexicon constrains our ability to design effective interfaces, an alternative perspective is that haptics should not necessarily mirror visual or auditory grammar, but should instead have a unique representational system (Culbertson et al., 2018). One promising approach is to draw inspiration from tactile languages such as Braille or sign language, where meaning is conveyed through structured patterns of touch. Developing a standardized set of haptic signals—akin to the International Morse Code for auditory communication—could enhance the usability of haptic interfaces across different devices and contexts.

Crucially, achieving this standardization requires collaboration between researchers, designers, and industry stakeholders to establish common conventions for haptic encoding and interpretation. Designers and researchers should collaborate on defining a basic haptic vocabulary (for example, a short double buzz meaning “error,” or a long pulse meaning “loading”) that, if used consistently, users will learn to recognize across devices. In the near term, designers should at least maintain consistency within their products: the same haptic pattern should be used for the same event every time, and emerging industry guidelines for haptic icons should be followed.

Low replicability and fidelity of haptic feedback

A final set of challenges in haptic design relates to the replicability and fidelity of haptic feedback. Unlike graphical interfaces, which can be easily replicated across different screens, haptic experiences vary significantly depending on hardware capabilities, actuator precision, and individual perception. For example, the same vibration pattern may feel different on a smartphone, a gaming controller, or a smartwatch, depending on actuator quality, placement, and amplitude range (Okamura, 2004). This lack of consistency makes it difficult to create cross-platform haptic experiences that feel uniform and reliable. Ensuring consistency across devices remains an open challenge in haptic design.

High-fidelity haptic feedback is particularly critical in applications such as medical simulation and robotic surgery, where precise tactile sensations are necessary for skill development and operational safety (Wagner et al., 2002). Advances in high-resolution haptic displays and force-feedback systems have improved the realism of haptic simulations, but challenges remain in ensuring that these experiences translate effectively across different devices. One potential solution is the use of adaptive algorithms that dynamically adjust haptic feedback based on device-specific parameters, ensuring that users receive consistent sensations regardless of the hardware they are using (Petermeijer et al., 2015). However, achieving this level of fidelity requires continued advancements in both hardware and software integration.

Summary

The challenges discussed in this section highlight the complexity of designing user-centered haptic interfaces. From the uniqueness of perception and discoverability issues to the limitations of the haptic lexicon and fidelity concerns, each challenge underscores the need for a structured and intentional approach to haptic design. By applying principles of adaptability, discoverability, and multimodal integration, designers can create more intuitive and effective haptic interfaces. Furthermore, standardizing haptic communication and improving cross-device replication will be crucial for the future of haptic technology. As haptics continue to evolve, addressing these challenges will be essential in bridging the gap between theoretical frameworks and practical applications, ultimately leading to more immersive and meaningful haptic experiences.

By addressing these challenges through the strategies outlined above, haptic interfaces can be made more usable and user-centered based on the criteria of adaptability, meaningfulness, and immersion: adaptability can be addressed by personalizing feedback; meaningfulness can be addressed by developing a clear haptic vocabulary and intuitive mappings; and immersion can be addressed by integrating feedback smoothly into user actions and ensuring consistency. Next, I connect these practical strategies to broader HCI principles to further strengthen the user-centered approach.

A user-centered approach to haptic interface design

The challenges and solutions outlined for haptic design strongly align with classic HCI design principles. In fact, many principles that guide visual or auditory interface design have parallel importance in haptics. However—and importantly—their implementation must account for the tactile medium's unique characteristics. In this section, I discuss several key principles and theories and how they inform a user-centered approach to haptics.

When discussing a user-centered approach to computer interface design, it is difficult to begin anywhere other than Don Norman's (2013) foundational work, *The Design of Everyday Things*. In the book, Norman identifies six key design principles: visibility, feedback, constraints, mapping, consistency, and affordance. However, when these principles are applied to haptic interfaces, a fundamental issue emerges—haptic interactions are inherently invisible. Unlike visual interfaces, where elements can be seen and manipulated directly, haptic interfaces lack an immediate perceptual presence. This invisibility raises the question: How can designers create haptic interfaces that maintain a level of discoverability akin to graphical user interfaces?

A crucial part of addressing this challenge involves reconsidering affordances, a concept first introduced by Gibson (2014). Gibson proposed that an environment reveals to an animal all possible actions that are physically achievable. Norman (2013) later adapted this concept for interface design, arguing that affordances should be perceptible to users. In the case of haptic design, the problem is twofold. First, users must be able to discover haptic affordances without prior knowledge. Second, once discovered, those affordances must be interpretable, providing clear mappings between actions and outcomes.

This challenge is further complicated by cognitive load—the mental effort required to process information during an interaction. Overuse of haptic cues can overwhelm users, making interfaces difficult to navigate. This issue aligns with Hick's Law (Hicks, 1952), which states that the time required to make a decision increases logarithmically with the number of choices presented. Applying this principle to haptic design, excessive or ambiguous feedback can slow user response times and create confusion. Instead, haptic feedback should be carefully curated, ensuring that signals are meaningful, distinct, and task-relevant (Shannon, 1948). Endsley (1995) similarly emphasized the importance of prioritizing feedback appropriately, ensuring that it aligns with user expectations and cognitive processing capabilities.

One strategy for improving haptic interfaces is to align mappings with natural user expectations. Research on motor control and perceptual psychology suggests that mappings should reflect real-world physics and user intuition (MacLean, 2000). For example, a virtual steering wheel should provide progressive resistance as the user turns, just as a real-world steering system would. This approach supports task immersion, where feedback mechanisms reinforce an interaction's realism and engagement.

Additionally, haptic cues should not operate in isolation. Oviatt (2007) highlighted the benefits of multimodal interaction, where haptic feedback is complemented by auditory and visual signals. Studies on multimodal design suggest that when multiple sensory modalities reinforce the same message, cognitive load is reduced, and user comprehension improves (Srinivasan & Basdogan, 1997). For instance, a notification system that combines a vibration with a visual alert ensures that the message reaches the user effectively, even in situations where one modality may be compromised (e.g., a visually impaired user or a noisy environment).

Furthermore, feedback must be tightly coupled to user actions (Fitts, 1954). Delays in response time can lead to a sense of detachment from the interface, diminishing usability. High-fidelity haptic feedback should reflect user input in real-time, providing immediate confirmation of an action. This principle is particularly critical in fields such as robotic surgery and virtual reality, where precise, low-latency haptic responses are necessary for effective performance (Wagner et al., 2002).

Visibility and affordances

Don Norman's (2013) foundational principles for design include visibility of system status and perceivable affordances for possible actions. Haptic interfaces inherently challenge these ideas because by nature, touch feedback is invisible. A user cannot see a vibration or force until they feel it. This makes discoverability a top concern; as noted in the previous section, users often need cues to find haptic features. In terms of affordances, Gibson's (2014) concept of affordance (as adapted by Norman) is that objects should suggest how they can be used. For haptics, the question becomes: How can designers indicate that a touch-based action is available? One approach is using signifiers—visible cues or prompts—to accompany haptic elements. For instance, a slight raised texture on a touchscreen or a visual icon can prompt users to "press here for vibration." Ensuring haptic affordances are perceptible may also mean using training wheels (i.e., a brief on-screen message such as "Try pressing harder for feedback"). In essence, designers must compensate for haptics' invisibility by borrowing from other modalities or incorporating very clear physical design elements to serve as signifiers (e.g., distinct textures or shapes that invite touch). Doing so adheres to Norman's principle that the user should never be left guessing what actions are possible.

Feedback and constraints

Another of Norman's principles is providing clear feedback for each user action, and adding constraints to prevent errors. Haptic feedback is feedback by definition; it is a response to an action, so its presence supports this principle. However, the feedback must be designed to be noticeable and informative. If a user performs an action (like toggling a switch in VR) and the haptic response is too subtle or ambiguous, the principle is violated. By applying the proposed framework, designers can ensure feedback is within perceptible ranges (domain of the natural) and context-appropriate (domain of the artificial) so that it serves as a clear acknowledgment of the user's input. Regarding constraints, haptic interfaces can benefit from physical constraints (domain of the physical) to guide users. For example, the shape of a haptic device can make some interactions natural and others impossible, streamlining the experience—a grooved slider that only moves in one dimension both provides tactile feedback and prevents wrong moves. In addition, constraints in software (domain of the virtual) can limit haptic output to safe, expected ranges (preventing, for example, a sudden extreme force). Together, these considerations help ensure that the user experiences tactile feedback that is predictable and appropriate, preventing confusion or error from unexpected sensations.

Cognitive load: Hick's law and information theory

Users have limited cognitive resources, and overloading them with too much information (in any modality) leads to poorer performance. Hick's Law (Hicks, 1952) quantifies how decision time increases with the number of choices or stimuli. In the context of haptics, this implies that if designers present users with too many different haptic signals or a very complex tactile "language" to decipher, it will slow them down and cause confusion. For example, if a smartphone used a completely different vibration pattern for every single type of notification (message, email, app update, social media, etc.), users would be overwhelmed trying to remember them. A better approach is to use a small, manageable set of distinct haptic cues, each carrying a broad category of meaning (much as traffic lights use just three colors to convey all necessary states).

This aligns with Shannon's (1948) information theory, which would advocate maximizing information transfer while minimizing unnecessary signals—essentially keeping haptic messages concise and distinct. Limiting the repertoire of haptic signals to those that matter most (and designing them to be easily distinguishable) reduces cognitive load on the user. Endsley's (1995) theory of situation awareness also supports this: to maintain a user's awareness in a system, designers should prioritize and present only the most relevant information at any given time. In haptic terms, this means critical feedback (like an alert vibration) should take precedence and be unmistakable, whereas secondary feedback can be more subtle or omitted if it risks cluttering the sensory channel. The user's brain should not be forced to decode multiple simultaneous vibrations or remember long vibration codes under pressure.

Mapping and consistency: Natural mapping and Fitts's law

Mapping refers to the relationship between a control and its effect. A natural mapping is one that corresponds intuitively to real-world experience. For example, turning a steering wheel clockwise makes a car turn right; this natural mapping leverages our expectation of wheel behavior. In haptic design, maintaining natural mappings greatly enhances immersion. If a user scrolls down a list on a touchscreen and the haptic feedback mimics the friction of a physical scroll wheel, the interaction feels coherent. Research suggests that haptic feedback should, whenever possible, reflect real physical behaviors or metaphors that users understand. For instance, increasing resistance on a virtual dial as it reaches a limit is a mapping that signals the end of a range, similar to a physical dial that cannot turn further (e.g., the maximum level on a volume knob). Maintaining consistency in these mappings across an interface (and even across different interfaces) is important so that users form correct expectations. This reduces the learning curve and avoids surprises, aligning with Norman's (2013) consistency principle.

Moreover, coupling haptic feedback tightly with user actions is critical. This insight relates to Fitts's Law (Fitts, 1954) and general principles of responsiveness. Users should feel the consequences of their actions immediately and proportionally. Any delay or mismatch (such as a noticeable lag between pressing a button and feeling the click, or weak feedback in response to a strong action) can break the sense of direct manipulation. In high-performance contexts, even a few milliseconds of delay can degrade the user's sense of control. Thus, the system should aim for low latency haptic feedback, which modern hardware and software must optimize (e.g., via high update rates and fast actuators). Quick, consistent feedback also adheres to Fitts's Law by supporting rapid, subconscious control. The user should not have to stop and wonder if their action registered; they should feel it immediately, which encourages fluid interaction. This is especially crucial in applications like robotic surgery (Okamura, 2004; Okamura, 2009) or vehicle controls (Petermeijer et al., 2015), where the operator relies on instant tactile cues to perform precise movements.

Multimodal redundancy

Human perception works best when multiple senses reinforce the same message. For example, we often both see and hear a notification (a visual flash and a beep). Incorporating multimodal feedback in interface design is a well-established practice, and it is particularly helpful for haptics due to their silent, unseen nature. Oviatt (2007) and others have shown that combining modalities can reduce cognitive load and increase comprehension.

For a user-centered haptic design, this means that designers should rarely rely on touch alone to convey critical information. Instead, haptics should complement visuals and audio. A phone on silent mode uses vibration (haptic signal) to replace sound; in this situation, combining a visual signal (screen notification) with a haptic signal increases the likelihood of the user noticing the event. In a car's navigation system, a steering wheel vibration might indicate a lane departure, but a blinking indicator on the dashboard reinforces it visually. Multimodal design also aids accessibility: for users who cannot see well, it is vital to combine haptics with audio signals; for users who cannot hear, it is crucial to combine haptics with visual cues. Designing redundant cues (where touch feedback aligns with what a user sees or hears) can create a more robust and intuitive user experience. The framework's artificial domain emphasizes that context matters. If one sense is compromised (a user in a noisy environment might miss a sound, a user in VR might not see a real-world warning light), haptics can fill the gap, and vice versa. Ultimately, synergy between modalities leads to better situation awareness and user confidence.

Summary

In summary, traditional HCI principles—visibility, feedback, affordances, consistency, cognitive load management, natural mapping, multimodal support—all have direct applications in haptic interface design. The solutions I have proposed to address haptic challenges (adaptive intensity, multimodal cues, intuitive gesture integration, standardized patterns, immediate feedback) each tie back to these principles. By explicitly grounding haptic design decisions in user-centered theory, designers can ensure that technologies address users' needs and align with their mental models. Designers should continuously ask several questions: Is this haptic cue understandable? Is it necessary? Does it correspond to what the user expects? Is it helping the user achieve their goal? If these answers align, the haptic design is likely on the right track.

Addressing the challenges of haptic interface design requires a holistic, user-centered approach that integrates principles from perceptual psychology, cognitive science, and interaction design. By structuring haptic design around discoverability, affordance, and feedback optimization, designers can create interfaces that are not only functional, but also intuitive and immersive. Moving forward, standardization efforts, adaptive haptic rendering, and multimodal reinforcement will play crucial roles in shaping the next generation of haptic technology. Ultimately, well-designed haptic interfaces should be adaptable to individual user needs, cognitively efficient, and seamlessly integrated into broader interface ecosystems.

To create a well-structured approach to haptic interface design, it is useful to differentiate between two primary areas: (a) the design of the physical artifact (the tangible component of the interface), and (b) the design of the feedback it produces (the dynamic responses generated during interaction). This distinction aligns with the four-domain framework proposed in Chapter 2. The physical artifact is represented in the domain of the physical, where mechanical components such as textures, force-resistance mechanisms, and structural ergonomics shape passive haptic feedback. This includes ensuring that buttons afford pressing, that surfaces communicate texture intuitively, and that controllers fit naturally in the user's hand. This aligns with the concept of discoverability—the extent to which haptic interactions are intuitively learnable through natural exploration. On the other hand, the feedback generated by the interface is represented in the domain of the virtual. Here, dynamic feedback is introduced, transforming passive interactions into adaptive, meaningful responses. This includes features such as varying vibration intensity based on user input, modulating resistance dynamically, or encoding information through haptic rhythms (MacLean & Hayward, 2008). However, this domain extends beyond just feedback—it also encompasses how the user interprets and reacts to the information provided by the interface.

In the sections that follow, I discuss haptic design considerations associated with these two major areas.

Understanding the user

Haptic perception varies across the body due to differences in mechanoreceptor density, skin elasticity, and anatomical function (Grunwald, 2008; Lederman & Klatzky, 2009). While hands and fingers have traditionally dominated haptic interface design, expanding feedback beyond these regions offers new opportunities for wearables, immersive systems, and accessibility applications (Culbertson, Schorr, & Okamura, 2018). In this section, I outline six primary haptic regions, examining their sensitivity, functionality, and interaction potential.

The human sense of touch and haptic perception are experienced through the largest organ of the human body: the skin. However, skin is not uniform in structure or function. Some areas are highly elastic, particularly around joints, where the skin must stretch and bend to accommodate movement. In other regions, such as the glutes, the skin overlays dense muscle, whereas in areas like the shins or the top of the head, it is tightly stretched over bone, offering little cushioning. These structural differences influence the distribution of mechanoreceptors and result in significant variations in haptic sensitivity across the body (Grunwald, 2008; Lederman & Klatzky, 2009). For example, the fingertips and lips contain a high density of mechanoreceptors, making them exceptionally sensitive to tactile stimuli, whereas regions such as the back have lower receptor density and are less perceptive to fine details (Jones & Lederman, 2006; Klatzky & Lederman, 1999). Understanding these variations is crucial for the design of haptic interfaces, as different regions of the body respond differently to various forms of haptic stimulation.

Designers must account for these disparities to ensure that haptic feedback is perceivable and meaningful, optimizing placement, intensity, modality, and duration of haptic interactions.

Historically, the development of haptic technologies has focused on the hands and fingers. Fine motor control and high tactile sensitivity make our hands and fingers ideal sites for precise interactions with digital interfaces (Hayward & MacLean, 2007; Klatzky & Lederman, 1999). This emphasis has led to significant advancements in finger-based haptic feedback, such as vibrotactile actuators in touchscreens and force-feedback controllers for virtual environments. However, as haptic research progresses, there is growing recognition of the potential to expand haptic feedback beyond the hands to other areas of the body, broadening the scope of wearable haptic devices, whole-body feedback systems, and virtual experiences (Culbertson, Schorr, & Okamura, 2018; MacLean, 2000).

Different regions of the body exhibit varying levels of sensitivity and perceptual resolution, making it essential to identify underutilized areas for haptic interaction and assess their viability for feedback integration (Grunwald, 2008). By strategically mapping haptic interactions onto regions with optimal sensitivity for specific applications, designers can enhance accessibility, usability, and immersion in domains such as virtual reality, assistive technology, and teleoperation (Culbertson, Schorr, & Okamura, 2018). These mappings can offer designers further guidance on leveraging multimodal haptic feedback—combining tactile, kinesthetic, and proprioceptive stimuli—in different regions of the body. Doing so can improve user engagement and performance in complex interactive systems (Biggs & Srinivasan, 2002).

In this section, I categorize the human body into six primary haptic regions: hands and fingers, arms and wrists, torso and back, legs and feet, face and head, and ears (Figure 3-1). These classifications are based on relative sensitivity, surface area, mobility, and anatomical proximity, as different regions of the body are uniquely suited for specific haptic applications. Some areas, such as the hands, excel in fine tactile feedback, while others, like the torso, are more suitable for broad, low-resolution feedback. In the subsections that follow, I explore how haptic interfaces have been designed and applied across these regions of the body, identifying established implementations, underutilized opportunities, and emerging directions in haptic technology. I conclude by providing a summary table that synthesizes key attributes of each body region.

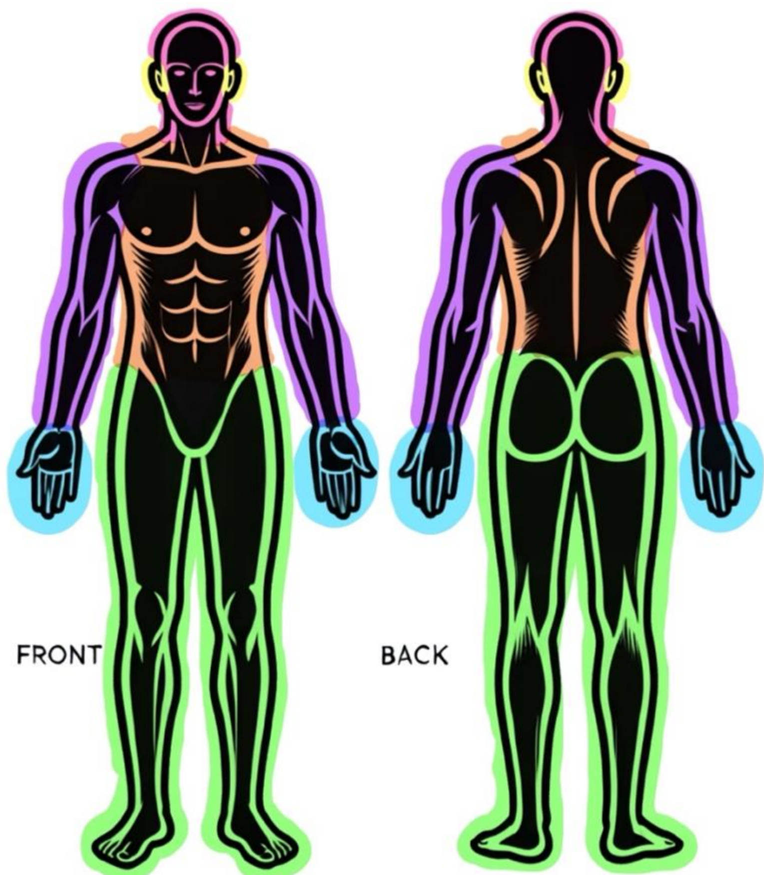

Figure **3-1**: Haptic regions of the body.

Note. Colors indicate different haptic regions of the body: blue - hands and fingers; purple - arms and wrists; pink - face and head; green - legs and feet; orange - torso and back; yellow - ears.

Hands and fingers: The epicenter of haptic interaction

The hands and fingers serve as the primary interface for haptic interactions, given their high mechanoreceptor density, fine motor control, and active exploratory function (Johansson & Vallbo, 1979; Lederman & Klatzky, 2009). Unlike other regions of the body, the hands not only receive haptic feedback but also actively manipulate and explore objects, making them the dominant for digital interactions, gaming, teleoperation, and assistive technologies (Johansson & Flanagan, 2009; Okamura, 2009).

Gibson's (1962, 1979) ecological theory of perception emphasizes that haptic perception is an active process, where individuals explore objects through coordinated hand movements to extract meaningful information rather than passively receiving tactile stimuli. According to Gibson (1979), haptic perception is fundamentally exploratory, meaning that haptic gloves must support natural exploratory behaviors such as rubbing, pressing, and grasping. This perspective highlights the importance of ergonomically designed gloves that allow for free hand movement while delivering realistic haptic feedback. This means that haptic interactions designed for the hands must account for both tactile reception and active exploration, ensuring users can probe, manipulate, and refine their perception through movement. The high concentration of Meissner's corpuscles (light touch) and Pacinian corpuscles (vibration) within the small surface area of the fingertips allows users to easily detect textures, pressure differentials, and micro-vibrations, making them ideal for applications requiring precise feedback and nuanced control (Johansson & Vallbo, 1979). As a result, the hands have been the primary focus of haptic technology development, leading to innovations in gaming, mobile interfaces, and immersive virtual environments.

Haptic interfaces designed for the hands and fingers have evolved significantly. Gaming controllers, touchscreens, and VR gloves leverage vibrotactile, force-feedback, and texture-based stimuli to enhance immersion and interaction precision (Burdea, 1999; Linjama & Kaaresoja, 2004). In gaming, modern controllers such as the Sony PlayStation and Microsoft Xbox incorporate adaptive triggers and vibrotactile actuators to provide realistic resistance, terrain texture, and motion dynamics, enhancing user immersion in interactive environments (Burdea, 1999). Beyond gaming, haptic feedback is a core element of modern touchscreen interfaces, where vibrotactile cues simulate button presses and other controls, improving user experience (Linjama & Kaaresoja, 2004). Apple's Taptic Engine and Android's haptic capabilities refine interactions by modulating vibration intensity and frequency, allowing users to perceive variations in pressure and force application.

The future of hand-based haptics lies in advanced texture simulation, variable resistance actuation, thermal feedback, and improving realism in VR, remote robotics, and assistive technologies (Beattie et al., 2020). One major research direction is advanced texture simulation, where haptic interfaces aim to replicate the tactile properties of real-world surfaces. Current haptic gloves provide only basic textural feedback, but emerging electrotactile and ultrasonic haptic systems are enabling finer surface differentiation, roughness detection, and material recognition (Beattie et al., 2020). Additionally, machine learning-driven haptic rendering is being explored to improve real-time texture replication by leveraging databases of physical materials, allowing users to experience textures with unprecedented accuracy.

Another critical area of research is pressure-sensitive interactions and high-fidelity variable resistance feedback. Traditional haptic gloves rely on fixed resistance levels, but next-generation devices are exploring materials with variable stiffness to create dynamic force feedback to simulate weight, elasticity, and material resistance. Hydraulic or pneumatic actuation systems are also being integrated into haptic gloves to enhance resistance-based feedback, making virtual interactions feel more natural and physically intuitive. These developments could significantly benefit VR training simulations, surgical skill development, and remote robotic control, where precise haptic perception is crucial (Okamura, 2004; Okamura 2009).

Another promising area of innovation is thermal feedback, which remains largely unexplored in commercial haptic interfaces. While pressure and texture feedback have advanced significantly, most VR gloves and controllers do not incorporate temperature-based feedback, even though it plays a key role in real-world touch perception (Wilson, Brewster, & Hughes, 2013). Researchers are now experimenting with thermoelectric actuators that allow users to feel temperature variations in VR environments, enhancing realism in gaming, medical training, and industrial simulations. For example, surgical simulations could incorporate thermal cues to replicate the sensation of touching body tissue at different temperatures, improving the fidelity of medical training applications.

The integration of haptics in virtual reality has also led to the development of haptic gloves, such as HaptX, TESLAGLOVE, and SenseGlove, which incorporate force feedback actuators and pressure sensors to simulate gripping, squeezing, and texture perception (Culbertson, Schorr, & Okamura, 2018). Some advanced models, like the Dexmo Exoskeleton Gloves, apply resistive force to individual fingers, enabling users to “feel” the weight, texture, and resistance of virtual objects. Soft robotics-based gloves provide a more naturalistic force distribution, improving precision manipulation in VR, teleoperation, and remote surgical applications (Okamura, 2009).

Arms and wrists: wearables

The arms and wrists are well-suited for wearable haptics, where vibrations, pressure feedback, and kinesthetic cues provide movement guidance and real-time interaction support

(MacLean, 2000). Smartwatches, prosthetics, and exoskeletons integrate directional haptic cues for navigation, fitness tracking, and rehabilitation. Future developments focus on adaptive force-feedback wearables that assist with motion correction, prosthetic control, and gesture-based computing.

Torso and back: Large-area feedback for immersion and awareness

While less sensitive than hands, the torso and back are prime candidates for broad, low-resolution haptic interactions. Haptic vests and suits (e.g., Teslasuit, bHaptics) provide impact feedback in VR, while posture-correcting wearables offer subtle haptic nudges for ergonomic adjustments (Culbertson, Schorr, & Okamura, 2018). Future applications include haptic-enhanced seating for automotive alerts, training simulations, and passive awareness cues.

Legs and feet: Underexplored in consumer haptics

Though often overlooked, the legs and feet provide valuable opportunities for gait feedback, balance correction, and haptic navigation. Rehabilitation devices use vibrotactile actuators to train movement patterns, while experimental VR footwear simulates terrain and weight distribution changes. Future innovations cite could explore foot-based haptic controllers (e.g., RAT computer device that serves as a mouse for the feet) and assistive haptics for visually impaired navigation.

Face and head: High sensitivity, minimal development

The face and head, though highly sensitive, remain an underutilized area in haptic research. VR headsets have begun incorporating micro-vibrations to enhance spatial presence, while bite-based haptic interfaces (e.g., BiteBar) offer speech therapy and accessibility solutions (Wilson, Brewster, & Hughes, 2013). Emotional haptics, such as facial touch-based feedback for social interactions, could shape the future of immersive communication. Other opportunities include haptic-assisted AR/VR and haptic-assisted speech therapy.

Ears: Crossroads between audio and haptics

The ears serve as a bridge between haptic and auditory feedback, particularly in bone-conduction hearing aids, vibrotactile music perception, and immersive sound integration (Oviatt, 2007). Innovations in tactile audio cues could enhance spatial awareness, accessibility for the hearing impaired, and immersive media experiences.

Summary

While hand-based haptics continue to dominate, mapping haptic interactions across the body presents unexplored opportunities for accessibility, immersion, and usability. By considering sensor distribution, interaction context, and multimodal integration, future haptic interfaces can deliver more inclusive and contextually optimized experiences. I summarize the primary haptic functions of different sections of the body in Table 3-1.

Table **3-1**: Primary haptic functions of different sections of the body.

Body section	Surface area	Mobility	Sensitivity	Primary haptic function	Receptor type dominance
Hands and fingers	Low	Very high	Very high	Tactile exploration, precise manipulation	Meissner's corpuscles (fine touch), Pacinian corpuscles (vibration)
Arms and wrists	Low	High	High	Wearable haptics, gesture-based control	Merkel cells (pressure), Ruffini endings (stretch)
Torso and back	Very high	Low	Low	Large-area feedback, directional cues	Pacinian corpuscles (vibration), Ruffini endings (stretch)
Legs and feet	High	High	Medium	Gait feedback, mobility haptics	Proprioceptors (balance), Merkel cells (pressure)
Face and head	Medium	Medium	Very high	Facial interfaces, headgear	Meissner's corpuscles (fine touch), Thermoreceptors (temperature)
Ears	Very low	N/A	High	Bone-conduction and auditory-haptic integration	Cochlear mechanoreceptors (bone conduction)

Designing feedback

Physical design choices impact the effectiveness of haptic interfaces and help users develop an initial understanding of how to interact with them. Ultimately, feedback is the most important design element that guides users as they complete tasks and helps them achieve goals. To support effective user interactions, haptic feedback must be designed to satisfy three key criteria: adaptability, meaningfulness, and immersion.

Adaptable feedback

Haptic feedback should respond to different conditions and user behaviors. For example, a virtual knob might increase resistance the faster it is turned (simulating inertia), or a smartphone might escalate vibration intensity if the user fails to notice the first gentle buzz of an alarm. Adaptable feedback often relies on sensor inputs and state changes. It is enabled by algorithms (in the virtual domain) that can modulate actuator output. Prior work like TeslaTouch demonstrated dynamic friction feedback on touchscreens that changes as users slide their fingers, providing context-dependent tactile sensations (Bau et al., 2010). The goal is to make haptic feedback interactive, rather than one-size-fits-all. This increases usability by accommodating context (e.g., louder environments might trigger a stronger vibration) and personal preferences (e.g., by allowing user tuning).

Meaningful feedback

Each haptic signal should convey information or reinforcement that users can interpret correctly. Designing meaningful feedback is akin to designing a language—it requires consistency and clarity. For instance, a short, sharp, double pulse might be chosen to signify a notification, whereas a long, gentle rumble could indicate a continuous process (e.g., a file transfer). If using multiple types of feedback in one device, signals should be distinct and purposefully mapped to events. To ensure users learn the meanings, initially pairing them with visual labels (multimodal) or using intuitive metaphors helps. For example, users may intuitively interpret a vibration that becomes more intense as akin to increasing pressure or intensity. As noted earlier in this chapter, establishing a haptic lexicon within each product (and ideally across products) is important. Feedback is meaningful when users do not have to think about what it means.

Immersive feedback

Especially in experiential interfaces (games, VR, simulations), the aim is to create a sense of presence or enhanced realism through touch. Immersive feedback means the tactile response is so well-integrated and lifelike that the user "believes" in the experience. This often involves richness of feedback (multiple actuators, high fidelity output) and coherence with other sensory outputs (as discussed with multimodality and natural mapping). For example, when a VR controller enables a user to feel the contour of a virtual object or the recoil of a virtual tool, it deepens the illusion of being in that virtual world. Emotional design also plays a role, as certain haptic patterns can elicit emotional reactions. For example, a gentle heartbeat-like vibration might induce calm, whereas erratic jarring might induce alertness or stress in a storytelling context. Immersive feedback design benefits from psychological insights associated with the artificial domain—that is, knowing what users expect and what will surprise or delight them. It also demands careful engineering to avoid breaking immersion: latency must be low, and feedback should be free of distracting artifacts (e.g., no unintended rattling or noise from actuators).

In implementing feedback design, one must also consider the limits and integration with the artifact. The best dynamic pattern is useless if the device's motor cannot reproduce it accurately or if the user's hand cannot feel it strongly. Thus, feedback designers should work hand-in-hand with artifact designers (haptic hardware engineers) to ensure feasibility. This process often unfolds in an iterative loop: an envisioned haptic effect might require tuning or even adding additional actuators/sensors to the artifact; conversely, a given hardware setup might inspire certain feedback capabilities (e.g., a device with a linear actuator can create a different sensation than one with an eccentric motor, leading to different design choices).

Bridging back to the framework, the domain of the artificial emphasizes the importance of validating feedback design with users. Usability testing is crucial: Do users perceive the feedback as intended? Do they notice it at the right times? Does it aid their tasks or enjoyment? Feedback design might need to be refined based on these insights, similar to how UI designers iterate on button layouts or color schemes. By applying user feedback, designers can close the loop of user-centered design in the haptic realm.

Summary

Overall, separating the concerns of artifact design and feedback design in haptics allows a clearer focus on each, but successful products will tightly integrate the two. A great device with poor feedback patterns will underperform, and brilliant haptic effects on badly designed hardware will falter. Using the four-domain framework, designers can ensure that the artifact (domain of the physical) is built on human capabilities (domain of the natural), and that the feedback (domain of the virtual) is crafted with an understanding of user interpretation (domain of the artificial). This structured approach leads to haptic interfaces that are not only technologically impressive, but also practically effective and satisfying to use.

Chapter 4

Conclusion: Feeling is Believing

The aim of this thesis was to strengthen the theoretical and practical foundations of haptic interface design. I achieved this aim by synthesizing research from multiple academic disciplines into a structured framework and applying that framework to develop a user-centered approach to haptic design. In the subsections that follow, I summarize primary contributions of this work, discuss practical implications for design, acknowledge limitations of the proposed framework and design approach, and highlight opportunities for future research.

Contributions

This work contributes to design theory and practice by: (a) developing a four-domain haptic framework; (b) identifying key user-centered haptic design criteria; (c) establishing a set of guidelines and heuristics for user-centered haptic design; and (d) distinguishing between artifact and feedback design. First, I synthesized the literature on haptics across multiple academic disciplines and proposed a novel framework categorizing haptic design into four key domains: the domain of the natural, the domain of the physical, the domain of the virtual, and the domain of the artificial. This framework provides a structured, comprehensive view of haptic interactions. Unlike prior fragmented approaches, it links biological limits, mechanical implementations, computational adaptivity, and user experience into a single model, helping designers and researchers understand how each layer contributes to the overall system.

Second, I identified three essential criteria for effective haptic interfaces—adaptability, meaningfulness, and immersion—and demonstrated how focusing on these can improve the user experience. Adaptability ensures that haptic feedback can adjust to different users and contexts, meaningfulness ensures that haptic feedback conveys useful information or cues, and immersion ensures that haptic feedback deeply engages users by feeling realistic and integrated. I used these criteria to develop targeted solutions for known haptic design challenges, from personalizing feedback to improving discoverability and consistency.

Third, building on the proposed framework and design criteria, I proposed a set of practical design guidelines (or heuristics) to aid in creating user-centered haptic interfaces. I outlined strategies to address several challenges currently constraining the design of haptic interfaces—e.g., allowing user calibration and using context-aware modulation to ensure adaptability, maintaining a consistent haptic "vocabulary" and intuitive mappings to ensure meaningfulness, and synchronizing multimodal feedback with real-time response to ensure immersion. These recommendations can serve as a reference for designers. I developed multiple heuristics (approximately three under each criterion) that encapsulate best practices (e.g., "ensure every haptic signal has a clear purpose the user can interpret;" "provide immediate tactile feedback to confirm user actions;" "use familiar metaphors or real-world analogues in haptic effects"). By following these guidelines, designers may be able to significantly enhance the usability of haptic systems.

Fourth, I distinguished between the two major elements of haptic interface design—the artifact (physical device) and the dynamic feedback it generates—and discussed how to optimize each. Articulating the considerations for artifact design (ergonomics, placement, mechanical structure) versus feedback design (signal patterns, timing, integration with context) provides a more nuanced understanding that can help practitioners systematically address both elements during the design process. I illustrated this approach by mapping artifact design to the domain of the physical, which inherently requires considering human capabilities (domain of the natural) and feedback design to the domain of the artificial, which inherently involves considering technological capabilities (domain of the virtual), thereby showing how each domain of the framework informs specific design decisions.

Implications for design

This work has important practical implications for design. The framework and user-centered approach from this thesis have the potential to shape the next generation of haptic technologies. Designers armed with a deeper understanding of human haptic perception and clear design principles can create interfaces that feel more intuitive, engaging, and trustworthy to users. For instance, instead of generic buzzes, consumer electronics may provide more context-aware and information-rich haptic cues that users can quickly learn and rely on, increasing the frequency of interactions and reducing the need to look at screens for feedback. In safety-critical systems like automotive interfaces or medical devices, improving the meaningfulness and consistency of haptic feedback can lead to better situation awareness. For example, a car seat that vibrates in a distinct pattern for lane departure versus a collision risk can convey urgency more effectively than a one-size-fits-all rumble. Such clarity can improve user responses and reduce errors.

Furthermore, immersive applications stand to gain tremendously. Virtual reality, gaming, and remote robotics (teleoperation) often suffer when haptic feedback is absent or too “low level” (simple vibrations), as it disrupts the user’s sense of presence or control. By implementing the immersive and adaptive feedback techniques described, designers can significantly enhance realism. Imagine VR environments where every interaction—from the slight resistance of a virtual door to different textures of surfaces—is conveyed to the user appropriately; this would blur the line between the virtual world and the real world, increasing the effectiveness of simulations for training or entertainment. As another example, surgical robots could use adaptive and meaningful haptic feedback to convey critical information about force and tissue texture to surgeons beyond what current simple force feedback provides, thereby improving precision and safety during remote operations.

In essence, the approach advocated in this thesis leads to more explainable and user-friendly haptic systems. Just as GUI design evolved from clunky command interfaces to intuitive graphical environments by focusing on user needs and cognitive factors, haptic interfaces can evolve from today's often rudimentary feedback to sophisticated, user-centered tactile communications. This evolution will be crucial as we integrate computing into more facets of daily life (wearables, IoT devices, augmented reality), as our eyes and ears may not be available to process additional signals. Touch can play a larger role if artifacts and feedback are designed correctly.

Framework and design limitations

While this thesis provides a structured framework for haptic design and contributes to the development of user-centered haptic interfaces, it does not resolve all challenges inherent to the field. The four-domain framework offers a theoretical model for understanding haptic interactions, identifying key limitations, and improving the design of haptic interfaces, yet it does not account for the full complexity involved in haptic perception, implementation, and interaction. In some cases, the design changes and heuristics proposed in this thesis may only serve to mitigate or obscure underlying issues rather than fully resolve them. Certain aspects of haptic interaction remain difficult to standardize or control, and technological and perceptual constraints continue to present challenges that cannot be fully addressed through design alone.

User limitations

The natural and artificial domains provide a conceptual framework for understanding user haptic perception, but they do not encompass every possible application. One limitation of this work is the exclusion of certain haptically relevant areas of the body. Regions such as the anus, groin, inside of the mouth, and inside of the nose were intentionally omitted from the conceptual framework. Although these areas are highly sensitive and thus technically applicable to haptic research, their relevance to the majority of haptic interfaces is minimal. Furthermore, sanitary concerns and a lack of established design literature for non-haptic interfaces in these regions further reduce their applicability. The primary haptic applications for the anus and groin are sex-related haptic devices, which fall outside the academic scope of this thesis. Similarly, the mouth and nose, while haptically sensitive, primarily serve as sensory organs for taste and smell. Future advancements in haptic technology may extend to these modalities, but at present, they remain peripheral to the core focus of haptic interface design.

Individual differences in haptic perception present another challenge. Haptic sensitivity varies not only across different body regions but also between individuals, making it difficult to design universally optimal haptic feedback. While I have suggested designing for an “average” user likely to interact with a given interface, there will always be outliers whose haptic perception falls outside standard ranges. The proposed solution of allowing users to adjust feedback intensity—similar to how auditory and graphical interfaces allow for volume or brightness adjustments—is a step toward addressing this issue. However, haptic perception is inherently more variable than auditory or visual perception, and providing a comprehensive range is not viable in many cases. As a result, haptic designers may still struggle to accommodate the full spectrum of perceptual differences among users.

Artifact limitations

While I explored a range of haptic feedback modalities in the domain of the physical, certain types of feedback remain outside the scope of this work. Specifically, nociceptive feedback (pain perception) and thermoreceptive feedback (temperature perception) were not extensively analyzed. Although these modalities could be integrated into future haptic interfaces, their inclusion presents unique challenges. Nociceptive feedback, by its nature, raises ethical considerations, as deliberately inducing discomfort or pain in users conflicts with standard usability principles. Thermoreceptive feedback, while promising, is currently limited by technological constraints and the inherent danger they present. Temperature-based haptic systems remain difficult to integrate safely into most interactive interfaces. Even when done safely, thermoreceptive feedback tends to be less effective for encoding information. Because of these limitations, I focused primarily on tactile and kinesthetic feedback mechanisms, which are more widely present and applicable in user-centered haptic design.

Additional technological constraints limit the fidelity of haptic sensations that can be replicated. In the domain of the virtual, I explored the simulation of haptic sensations; despite identifying user-centered approaches to improve haptic simulation, no design guideline can fully compensate for current hardware limitations in haptic rendering. Many existing haptic systems are restricted by actuation methods, latency, resolution, and material properties, making it difficult to achieve truly lifelike haptic experiences. Design can only compensate for so much until advancements in haptic hardware, material science, and actuation technology occur. The implementation of high-fidelity haptic interfaces will remain constrained by these physical limitations, leaving dynamic control of attributes like texture nearly impossible.

Interaction limitations

One of the most persistent challenges in haptic interface design is the lack of a standardized haptic lexicon, which continues to limit the amount of information that can be consistently encoded through haptic feedback. Unlike visual or auditory modalities, where structured systems such as alphabets, symbols, and phonemes provide a widely accepted framework for communication, haptic signals lack a comparable linguistic structure. As a result, users must rely on prior experiences, contextual cues, and experimentation to interpret haptic feedback, leading to potential inconsistencies in understanding and usability. While I have argued that creative and intentional design choices can improve haptic interpretability, these improvements remain incremental rather than absolute. Without a universally recognized haptic vocabulary, haptic designers will continue to face challenges in ensuring that feedback is meaningful across different interfaces and user populations.

Beyond issues of interpretation, active exploration remains a fundamental limitation of haptic interaction. Unlike visual or auditory interfaces, which provide users with passive access to information, haptic interactions typically require users to engage with an interface actively. This requirement introduces cognitive and physical demands that are not always present in other interaction modalities. Users must physically explore a haptic interface to perceive feedback, and this process varies significantly based on factors such as user skill level, prior experience, and individual perceptual differences. While I have acknowledged this challenge, I have not provided a definitive solution. Instead, I have developed strategies to mitigate the effort required in active haptic exploration.

Summary

The limitations outlined in this section do not diminish the contributions of this thesis; rather, they define the boundaries of its scope and highlight areas where further research is necessary. While the four-domain framework provides a structured approach to understanding haptic interaction, it does not address all challenges inherent to haptic design. Issues and limitations still exist for the user, system, and interactions involved with haptic interfaces. User variability in haptic perception, technological constraints, and the lack of a standardized haptic lexicon remain unresolved and are beyond the scope of this research. These limitations, however, underscore the need for continued investigation into haptic interface design.

Future work

This thesis opens several avenues for future research and development in the field of haptic interface design. Future work should focus on refining haptic interaction models, developing more advanced hardware, and establishing standardized frameworks that enhance the discoverability, usability, and learnability of haptic systems.

One priority is to further develop the haptic lexicon. Both academic and industry communities could benefit from collaborating to propose and test a set of standard haptic signals for common meanings. User studies involving participants representing a wide range of demographic characteristics would be needed to validate that these signals are indeed intuitive and distinguishable. Organizations similar to the W3C or ISO for haptics could be instrumental in driving standardization efforts.

Advancements in haptic hardware also will amplify what designers can do. Future work can focus on new actuator technologies that provide a wider range of sensations (for example, surface haptics that can dynamically change texture, or wearable haptics that cover larger areas of the body with fine control). With better hardware, some adaptability and immersion goals become easier to achieve, but this also requires updating the framework with new knowledge on how users perceive these novel sensations. For example, if ultrasonic-based mid-air haptics become mainstream, we would need to refine our understanding of the natural domain's limits in that context by answering questions such as: What is the resolution of mid-air touch perception? How do multiple simultaneous points of feedback integrate perceptually?

Another promising direction is leveraging AI and machine learning for haptic design. Just as AI has started to personalize visual content or speech interfaces, it could learn from user interactions to optimize haptic feedback in real time in accordance with the four-domain framework. For instance, a system might detect that a user consistently misses a certain haptic alert and automatically adjust its pattern to make it more prominent or pair it with another cue. Research into such adaptive algorithms could greatly enhance personalization beyond manual settings. Indeed, some researchers have already begun to explore this area.

In addition, it would be beneficial to explore haptic design for inclusive and accessibility-focused applications. Haptic interfaces have the potential to convey information to users who may not be able to see or hear well. In future studies, scholars could examine how the conceptual framework presented in this thesis applies to design processes targeting specific user groups. For example, considerations associated with the domain of the artificial may shift when touch is a primary sense rather than a secondary one. This could yield specialized guidelines that complement the general ones presented here.

Conclusion

In closing, the theoretical framework and user-centered approach to haptic design presented in this thesis could serve as steppingstones toward a richer, more "touch-literate" interaction paradigm. By rigorously studying haptic design and centering it on users, I have paved the way for interfaces where touch feedback is as intuitive and powerful as sight and sound in human-computer interaction. By enabling users to genuinely feel their digital interactions in meaningful ways, designers can make technology feel more natural and better integrate it into the human experience. The hope is that this work inspires further innovations such that one day, the absence of haptic feedback in an interface will be as noticeable as the absence of color or sound, and the design of haptic experiences will be guided by the same level of established knowledge and user-first thinking as other areas of design. With continued research and collaboration, the full potential of the haptic modality can be realized, adding a new dimension to how we interact with the world of computing. Today we say, "seeing is believing," but perhaps in the future what we feel will be as believable as what we see.

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