THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

COLLEGE OF INFORMATION SCIENCES AND TECHNOLOGY

Towards a Theory of Haptic Design

NOAH GEHMAN
FALL 2024

A thesis
submitted in partial fulfillment
of the requirements
for a baccalaureate degree
in Human-Centered Design and Development
with honors in Human-Computer Interaction

Reviewed and approved* by the following:

Fred Fonseca
Professor of Social and Organizational Informatics
Professor-in-Charge of Social and Organizational Informatics
Thesis Supervisor

Dan Welch
Assistant Teaching Professor of Human-Centered Design and Development
Thesis Honors Adviser and Faculty Reader

* Electronic approvals are on file.

ABSTRACT

This thesis proposes a foundational framework for a user-centered theory of haptic design by defining and analyzing systems, processes, and limitations of four foundational haptic domains: the domain of the natural (governed by principles of biology), the domain of the physical (governed by principles of physics), the domain of the virtual (governed by principles of computer science), and the domain of the artificial (governed by principles of psychology). The analysis of each domain reveals a key consideration of haptic design: haptic perception, passive haptic feedback, active haptic feedback, and haptic cognition. The four domains sequentially build on each other in such a way that the deficiencies of each domain are addressed by systems within the next domain. In the domain of the physical, mechanical systems address the deficiency of haptic perception in the domain of the natural by quantifying haptic sensations, enabling passive haptic feedback. In the domain of the virtual, computer systems address the deficiency of passive haptic feedback by dynamically simulating haptic responses, thereby enabling active haptic feedback. Finally, in the domain of the artificial, psychological systems address the deficiency of active haptic feedback by contextualizing user experience, thereby enabling haptic cognition. By analyzing the distinct yet interdependent roles of each domain, this thesis provides a framework that lends itself to a user-centered theory of haptic design which thus far has remained elusive.

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ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my thesis supervisor, Dr. Fonseca, for his invaluable support and guidance throughout this thesis. His passion for technology has inspired me to delve deeper into research, fostering a profound appreciation and curiosity that have shaped my academic pursuits.

I am also deeply grateful to Dr. Ritter for his vital contributions to this thesis. His expertise in cognitive psychology and human-computer interaction has been instrumental to my research on haptics. Being a member of the Applied Cognitive Science Lab under his supervision has provided me with an immense opportunity to grow as a researcher and develop essential skills in my field. The encouragement and guidance he has offered have helped shape not only this thesis but also my personal development.

I would like to thank Dr. Welch for his assistance in navigating the Schreyer thesis process. His guidance on deadlines and submission requirements has kept me on track and ensured that I met all necessary milestones for this project.

Last, but certainly not least, I would like to express my appreciation to my parents. Their unwavering support has been the foundation of my success, not only in this academic endeavor but in all aspects of my life. They have instilled in me the confidence and resilience needed to pursue my goals, and for this, I am forever grateful.

Chapter 1

Introduction

In *The Design of Everyday Things*, Don Norman (2013) noted that the field of design itself is still in its infancy and often poorly defined. He asserted that as a discipline, design is evolving as we grapple with the complexities of integrating human experience with engineering principles and practical applications. While this observation holds true for design in general, it is particularly relevant to the design of haptic computer interfaces.

Haptics refers to the science and technology of touch-related sensations, typically through feedback provided by a device or system that stimulates the sense of touch. It encompasses a range of mechanisms that allow humans to perceive, interpret, and interact with the world through tactile (skin-based) and kinesthetic (movement-based) sensations. Thomas Massie and J. Kenneth Salisbury (1994) developed the first haptic computer interface, PHANTOM, at MIT in 1993. Since then, the field of haptics has struggled to keep pace with advancements in graphic and auditory interface design. Whereas design principles and guidelines were quickly established in those fields, such design principles have yet to be established for haptics. If we were able to develop a theory of design for the other forms of computer interfaces, why has it been a struggle to do the same for haptic computer interfaces? Is it because we do not yet know enough about haptics?

In the field of physics, we have quantified our haptic perception to the same extent as vision and hearing—vision measured in terms of light wavelengths and color intensity, hearing in sound frequencies and decibels, and touch through force, vibration, and texture metrics

(Hayward & Maclean, 2007; Lederman & Klatzky, 2009). In computer science, we have similarly synthesized these sensory outputs: visual feedback is generated by displays, auditory feedback by speakers, and haptic feedback by actuators (Maclean & Hayward, 2008; Srinivasan & Basdogan, 1997). As a result, it is challenging to argue that our knowledge of physics or computer science limits our ability to create haptic design principles compared to other types of computer interfaces. From a biological standpoint, we have a deep understanding of how we can perceive things haptically, but the way we do this differs from how we perceive things visually or auditorily (Klatzky et al., 1987). Graphics and sound can be perceived passively, while haptic sensation, requires active exploration (MacLean, 2000). Gibson (1962) and Lederman & Klatzky (1987) define active exploration as the process by which an individual intentionally uses their hands or other body parts to manipulate, probe, and examine an object to gather information about its physical properties. Beyond this, in the field of psychology, the grammar we use to contextualize haptics is more abstract compared to the well-defined grammars we have for the things we see and hear (MacLean, 2000). I hypothesize that the well-documented differences between haptics, graphics, and sounds—specifically in how we discover their cues and the level of grammar required to contextualize them—have hindered the development of a generalized theory of haptic design. After all, how can we design interfaces to be discoverable through active exploration when such interfaces are inherently invisible? Moreover, even if these invisible interfaces were to be made discoverable to users, how could information be encoded in a way that is understandable without a precise and shared grammar to communicate it? At a minimum, any general theory of haptic design needs to be able to provide: (a) steps designers can follow to consistently make inherently invisible haptic interfaces discoverable to users, and (b) a more specific grammar through which information can be encoded to users. Additionally, as with most theories of design, a theory of haptic design should include design limitations, considerations, design patterns, and affordances, and should provide a user-centered approach.

Addressing these gaps by developing a theory of haptic design would constitute a meaningful contribution to the field of haptics, design, and human-computer interaction. A theory of haptic design that enables the development of well-designed haptic interfaces has the potential to be life-saving. In high-integrity fields like robotic surgery, where haptic feedback provides critical information about force and texture, poorly designed feedback systems could lead to fatal mistakes (Okamura, 2004). Conversely, well-designed haptic feedback systems could enable surgeons to perform more precise operations, saving lives in the process (Wagner et al., 2002). Similarly, in the automotive industry, a haptic steering wheel that vibrates if drivers begin to veer off course could prevent accidents, potentially saving the lives of both drivers and pedestrians (Petermeijer et al., 2015). Beyond life-saving applications, haptic design holds the key to creating more immersive virtual experiences. While current virtual reality systems have mastered visual and auditory immersion, they fall short in simulating realistic touch (Culbertson et al., 2018). Imagine a scenario in virtual reality where a user can not only see and hear a tiger, but also pet it and feel the texture of its fur. These examples demonstrate the potential that haptics holds, and how a theory of haptic design would have major implications for a broad range of industries, including medical technology, automotive safety, and virtual reality, to name a few. Given the myriad applications of haptic interfaces, addressing these gaps is the next frontier of computer interface design (Culbertson et al., 2018; Hayward & Maclean, 2007).

In this thesis, I aim to address these gaps by offering a new perspective on how to think about designing haptic interfaces. I conduct a comprehensive review of existing literature on both haptics and interface design and synthesize insights across these fields to develop a foundational framework for a theory of haptic design. Although there is limited direct research on haptic design as a unified field, the abundance of work on haptics and interface design, when combined with the existing literature on haptic design, offers a foundation for further progression towards a general theory of haptic design. Central to my framework is the assertion that there are four distinct domains of haptic design. By exploring these domains and explaining how they interrelate, I offer a structured approach that provides the basis for developing a theory of haptic design. Exploring these domains reveals constraints that must be taken into consideration when designing haptic interfaces.

The Four Haptic Domains

To develop a theory of haptic design, we must first acknowledge the existence of the four haptic domains, explore them individually in detail, and understand 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 1 provides an overview of the four haptic domains in sequential order and starts to show how they build on one another.

Table 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 off one another in two important ways. The first is by inheriting the limitations of the previous domain. Since limitations cannot be addressed, they must 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 off 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 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 provides a blueprint not only for how to succeed when designing haptic interfaces, but also reveals why some haptic interface designs fail.

Table 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

In the chapters 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 and gives 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.

The rest of this thesis is organized as follows. In Chapters 2–5, I describe and discuss each haptic domain in detail. In Chapter 6, I synthesize the key aspects of haptic design revealed by the four domains into a framework which can serve as an initial step toward a user-centered theory of haptic design, including design principles and guidelines to follow. In Chapter 7, I conclude with the findings of this thesis and explore future work that could be built off of them.

Chapter 2

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 chapter, 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 chapter 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 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.

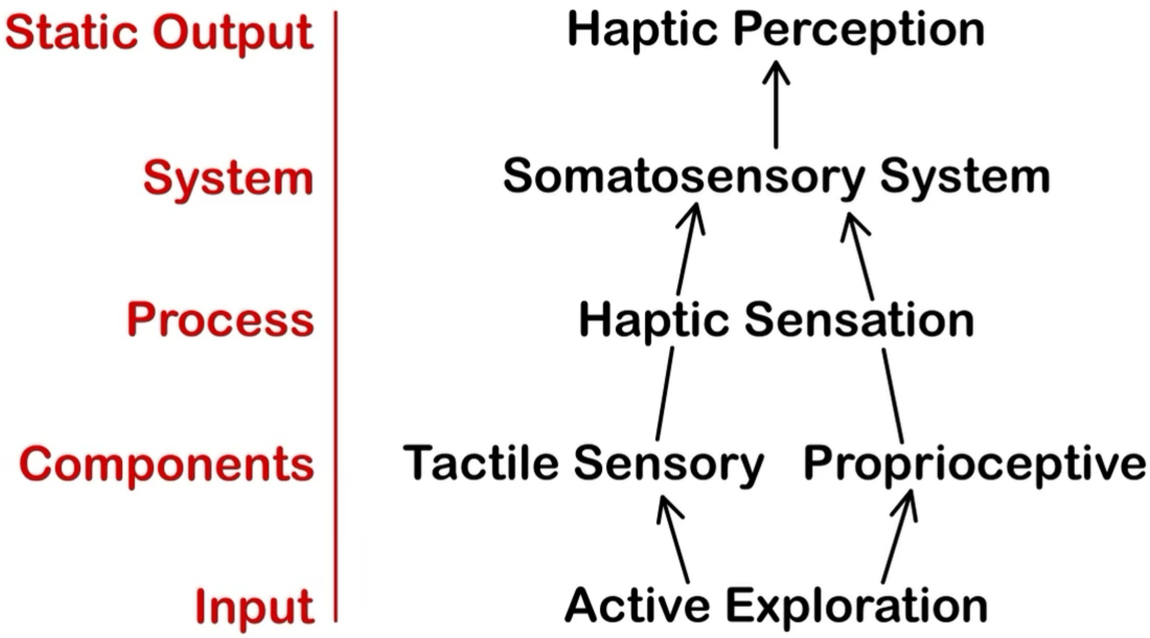

Figure 1. Somatosensory System Flowchart

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 the system exists in. 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 its 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. Our 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 chapter we will 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 our somatosensory system detects various environmental signals as haptic sensations. The components of the somatosensory system (i.e., components of detection) are crucial and enable our somatosensory system to create a model of haptic perception based on the haptic sensations it detects. 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 3.

Table 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 our somatosensory system and provide a foundational understanding of how we 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 (Grunwald, 2008; Dougherty, 2020). 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 chapters. 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.

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.

Chapter 3

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 chapter, 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 chapter 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, 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.

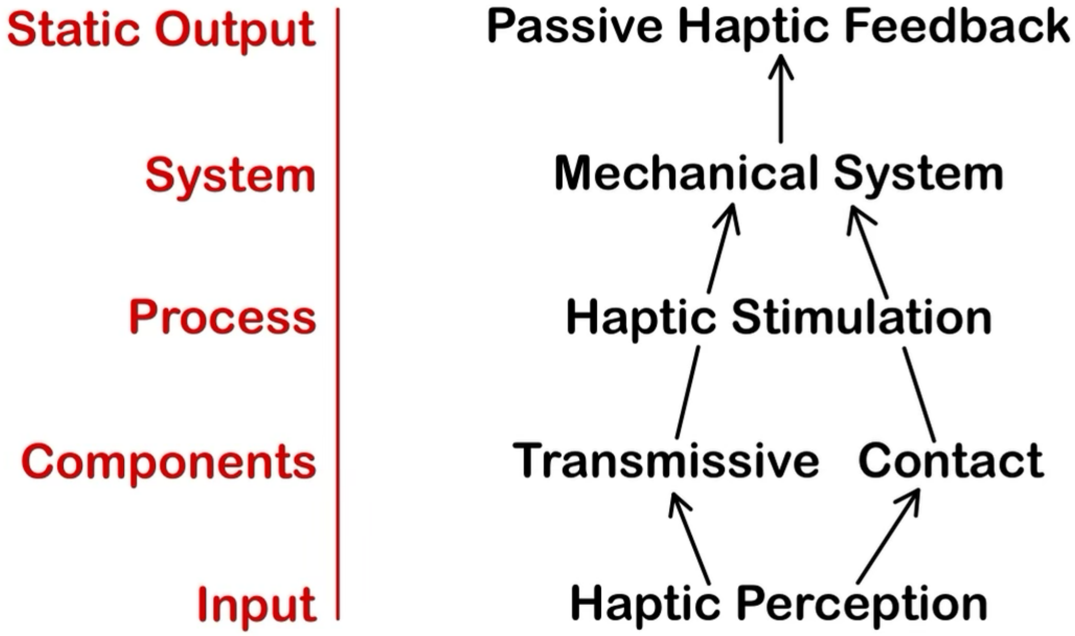

Figure 2. Mechanical System Flowchart

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 of 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 4.

Table 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 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 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 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/s^2)	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 chapter, 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. Overall, this chapter has provided a comprehensive overview of how haptic design can leverage mechanical systems to provide reliable but static feedback while identifying the limitations inherent to this domain.

Chapter 4

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 this domain, 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 chapter, 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 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.

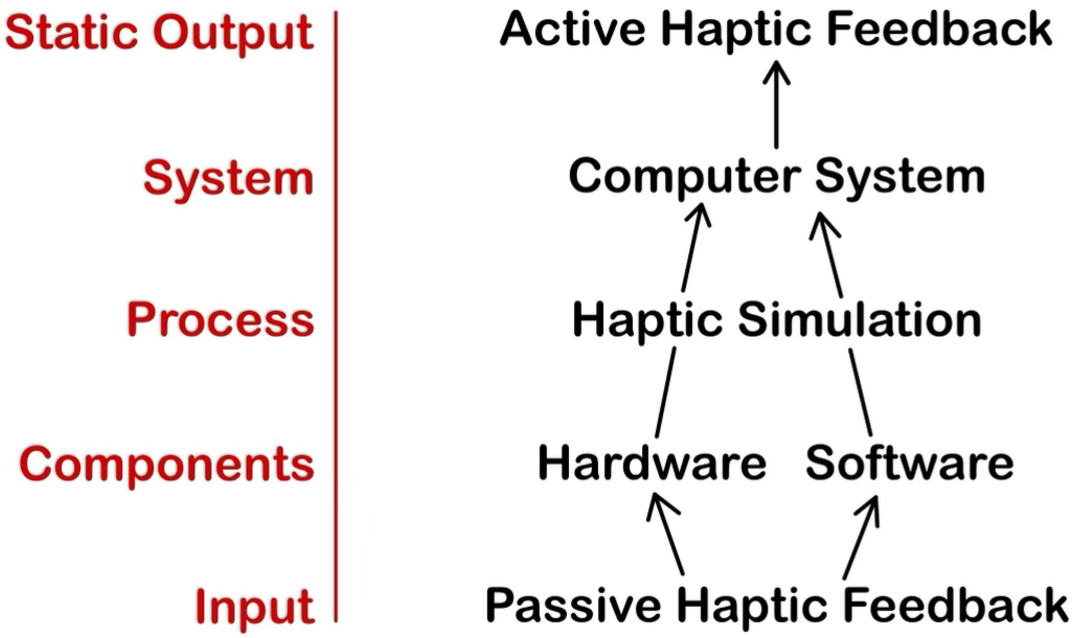

Figure 3. Computer System Flowchart

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 3 computer systems for haptics include both hardware (sensors, actuators) and software components that allow for the continuous adjustment of haptic stimuli. The 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 6.

Table 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.

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.

Chapter 5

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 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 by 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 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 this 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 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.

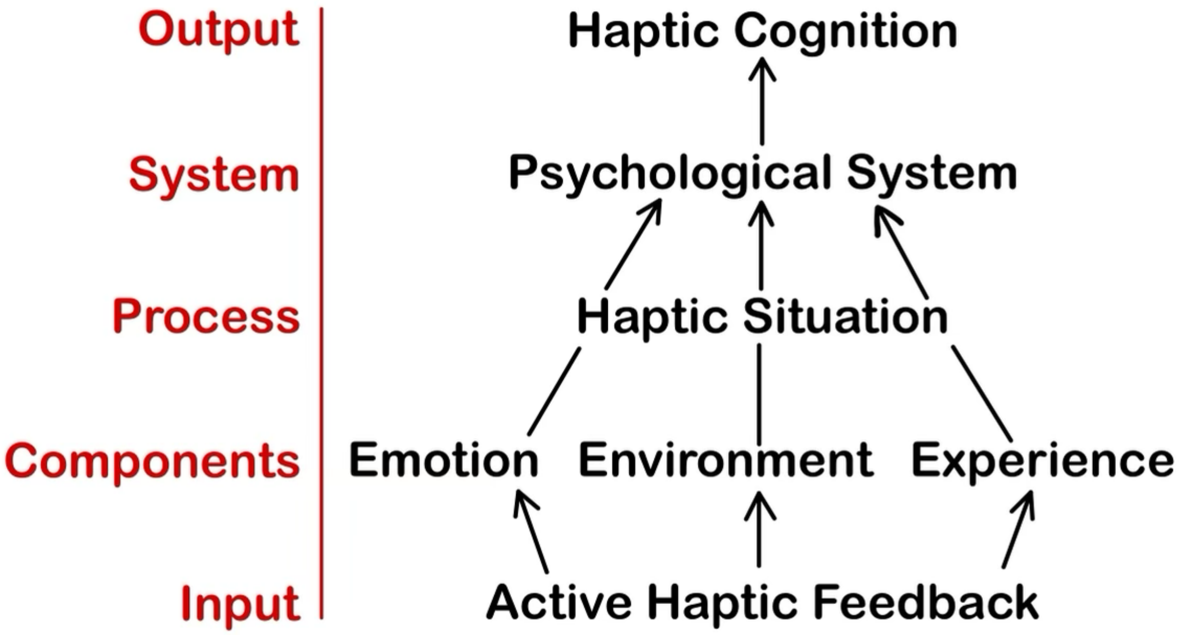

Figure 4. Psychological System Flowchart

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 rather gets 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 7.

Table 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.

Chapter 6

Toward a User-Centered Theory of Haptic Design

As the domains build on each other, we are primarily focused on constraints. That is, a desire to address design constraints is what drives the progression from one domain to the next. Once haptic cognition has been achieved, however, enough constraints have been addressed such that it is possible to develop a framework for user-centered haptic design. This can be accomplished by carefully analyzing the domains to identify which principles of design, patterns, and affordances each domain offers when taking a user-centered approach.

Key Takeaways from the Four Domains

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.

User-centered Design Considerations

A user-centered theory of haptic design also 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.

Framework for a User-Centered Theory of Haptic Design

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 5).

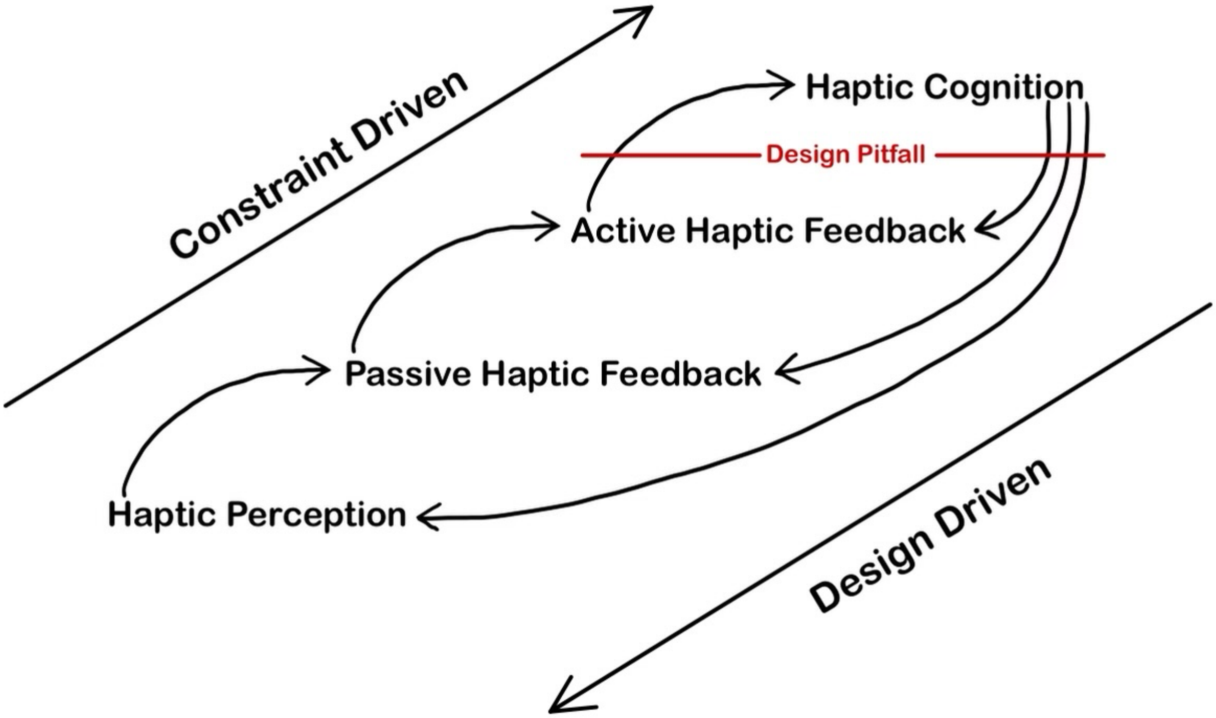

Figure 5. Framework for a User-Centered Theory of Haptic Design

This foundational framework for a user-centered theory of haptic design is based on my analysis of four haptic domains: the natural, physical, virtual, and 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, this thesis identifies 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 natural domain, the somatosensory system shapes haptic perception. In the physical domain, mechanical systems quantify haptic perception as passive haptic feedback. In the virtual domain, computer systems synthesize these interactions, dynamically simulating haptic responses as active haptic feedback. Finally, in the artificial domain, user experience is contextualized by psychological systems, fostering cognitive interpretation and situational adaptation. By analyzing the distinct yet interdependent roles each domain plays, this research contributes a novel approach to haptic interface design. My framework emphasizes a user-centered design strategy, combining principles of affordance, feedback, and immersion, ultimately aiming to support meaningful and accessible haptic experiences across a range of applications.

Chapter 7

Conclusion

In Chapter 1, this thesis introduced the need for a comprehensive theory of haptic design, highlighting the lack of established design principles for haptic interfaces compared to visual and auditory interfaces. Drawing inspiration from Don Norman's insights on design's infancy and recent work on haptic systems, I emphasized the unique challenges of haptic design, notably its need for active exploration. As one consequence, a theory of haptic design must address the invisibility of haptic interfaces and provide affordances that make interfaces discoverable and meaningful to users. To advance a theory of haptic design, I proposed the need to consider four distinct haptic domains—natural, physical, virtual, and artificial—each governed by a different field (biology, physics, computer science, psychology). I further posited that each successive domain built upon the previous domain to address its deficiencies. This layered approach aimed to reveal design principles and patterns essential for user-centered haptic design.

In Chapter 2, I explored the domain of the natural. This domain describes the foundational role of biology, specifically the human somatosensory system. It emphasizes tactile sensation and proprioception which serve as the basis for haptic perception by allowing humans to actively interact with their environment to experience touch, pressure, and body position. While acknowledging the system's biological constraints and limitations, I highlighted its essential importance to haptic design and discussed how understanding these constraints can guide the effective creation of haptic feedback systems in human-computer interaction. The chapter concluded by pointing out that future haptic design must consider these natural limitations while also developing methods for quantifying and simulating natural haptic sensations in higher domains.

In Chapter 3, I explored the domain of the physical. This domain describes how physics and mechanical systems provide a framework for quantifying haptic sensations, building on the biological basis set by the somatosensory system. This domain enables designers to transform haptic perceptions into measurable physical properties, delivering passive haptic feedback through mechanical components like gears, springs, and surface textures. Mechanical systems provide consistent, tangible feedback based on an object's inherent properties. However, these systems are limited by their inability to adapt dynamically to environmental changes. The chapter highlighted the importance of mechanical systems in creating reliable and predictable haptic feedback for devices but also noted the deficiency of passive haptic feedback when it comes to dynamically encoding information.

In Chapter 4, I explored the domain of the virtual. This domain describes how computer systems enable dynamic haptic feedback, building upon the static feedback of the physical domain. This digital domain, governed by computer science, transforms passive inputs into active, dynamic outputs, allowing for real-time adjustments in haptic sensations such as force, vibration, and texture. Virtual systems integrate hardware, like sensors and actuators, with software that processes and adjusts feedback based on user interactions, crucial for applications like VR, robotics, and gaming. However, these systems have limitations, including hardware, perceptual range, and latency issues, which can impact immersion and realism. The chapter underscores the significance of virtual systems in creating adaptable haptic experiences, noting that designers must balance these technological limitations to simulate interactive, lifelike sensations, while highlighting the deficiency of understanding users.

In Chapter 5, I explored the domain of the artificial. This domain describes the psychological aspects of haptic feedback, focusing on how users interpret and emotionally respond to the stimuli reviewed in the previous domains. Governed by psychology, this domain integrates inputs from natural, physical, and virtual domains, resulting in haptic cognition—a user's contextualized and emotional interpretation of haptic feedback. The chapter emphasizes that this interpretation depends on factors such as emotion, environment, and prior experience, which together shape users' cognitive responses to feedback. Although this domain helps bridge gaps left by physical and virtual feedback, it is limited by individual cognitive variability, which impacts the predictability of feedback interpretation. This chapter underscores the importance of designing haptic systems that align with users' mental models and emotional states, creating intuitive and user-centered haptic experiences that resonate with diverse psychological responses.

In Chapter 6, I synthesized insights from the four domains of haptic interaction—natural, physical, virtual, and artificial—to develop a framework focused on user-centered design. Building on each domain's constraints and affordances, this approach aims to guide designers in creating intuitive and meaningful haptic experiences. Key takeaways include respecting human sensory limitations from the natural domain, leveraging ergonomic principles from the physical domain, utilizing the adaptability of virtual systems, and incorporating user interpretations from the artificial domain. By applying Norman's (2013) principles, such as clear affordances, feedback, consistency, and discoverability, this framework encourages designs that are easy for users to navigate and interpret. The proposed user-centered theory emphasizes simplifying interactions and aligning feedback with users' goals and expectations, helping to establish a coherent foundation for haptic design that resonates with diverse user experiences.

Norman (2013) says interface designs should be enjoyable to users. This surfaces several questions for designers to consider: What kinds of haptic feedback do users find enjoyable? Which types of haptic feedback can be perceived? How can haptic feedback be quantified? What are we able to replicate in this range? Finally, within the ranges of haptic feedback that can be replicated, what levels of outputs do users enjoy? To answer these questions, we need to understand the constraints of haptic interfaces, which are limited by what we can perceive, quantify, synthesize, and contextualize. Insights from this research and my framework could support a better understanding of these constraints. In future research, this framework could inform the development of a robust theory of haptic design. In doing so, scholars could address a longstanding theoretical gap and help advance our understanding of haptics, thereby blazing a trail into the next frontier of computer interface design.

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