Haptic Fidelity Framework: Defining the Factors of Realistic Haptic Feedback for Virtual Reality

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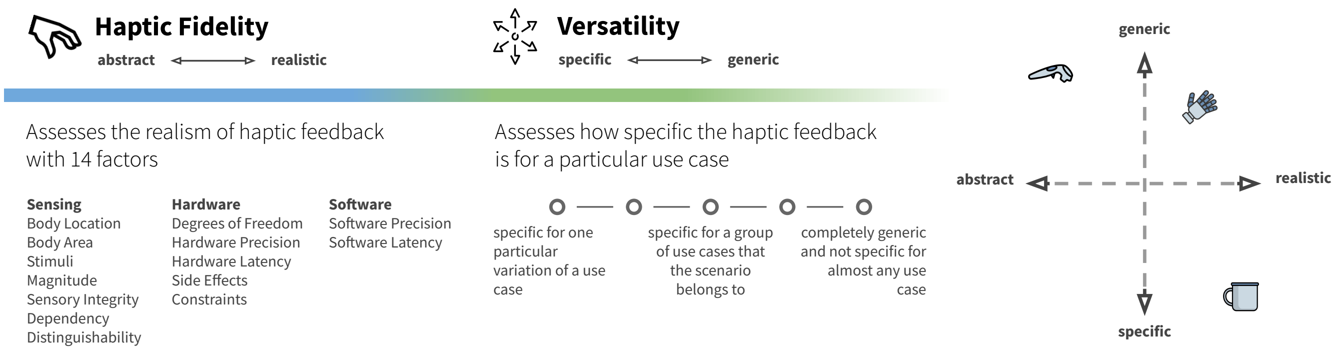

Figure 1: Overview of the two dimensions of the Haptic Fidelity Framework and classification of three examples in the dimensions of the framework for providing haptic feedback for a virtual mug: a standard VR controller with vibration, a force-feedback glove, and a real mug as passive haptic prop.

ABSTRACT

Providing haptic feedback in virtual reality to make the experience more realistic has become a strong focus of research in recent years. The resulting haptic feedback systems differ greatly in their technologies, feedback possibilities, and overall realism making it challenging to compare different systems. We propose the Haptic Fidelity Framework providing the means to describe, understand and compare haptic feedback systems. The framework locates a system in the spectrum of providing realistic or abstract haptic feedback using the Haptic Fidelity dimension. It comprises 14 criteria that either describe foundational or limiting factors. A second Versatility dimension captures the current trade-off between highly realistic but application-specific and more abstract but widely applicable feedback. To validate the framework, we compared the Haptic Fidelity score to the perceived feedback realism of evaluations from 38 papers and found a strong correlation suggesting the framework accurately describes the realism of haptic feedback.

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CCS CONCEPTS

• **Human-centered computing** → **HCI theory, concepts and models**; **Haptic devices**; • **Hardware** → **Haptic devices**; • **Computing methodologies** → *Virtual reality*.

KEYWORDS

framework, haptic feedback, haptics, feedback, virtual environment, immersion, realism, user experience, fidelity, versatility

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1 INTRODUCTION

Virtual reality (VR) aims to provide compelling experiences for users through immersive technology. Extending this experience with haptic feedback has become a strong focus in research in recent years, intending to create more realistic and engaging virtual environments (VE). One of the big challenges in this field is to create realistic and convincing feedback to simulate the real world or create experiences beyond what is possible in reality. As a result, a large variety of haptic feedback systems have been proposed ranging from standard VR controllers with vibration feedback [57] over custom build controllers simulating shape [74], weight [86], and forces [85] to electric muscle stimulation (EMS) [47], actuated robot arms [58], drones [26], and passive haptic props [53]. These systems differ considerably regarding their technologies, their goals, and approaches on how and where to provide feedback. This variety makes it challenging to compare systems, find comprehensive results in evaluations and inform the design of new systems. Researchers and designers of haptic feedback systems benefit from systematic information on factors influencing the perception of haptics and how the system design relates to these factors. Providing a structured framework that incorporates the underlying mechanics gives them the opportunity to analyze feedback systems and reveal potential for new designs. Current frameworks either focus on the user experience [38], target specific types of feedback, e.g., vibration feedback [54], or propose physical measures that only apply to certain types of feedback systems [59]. To the best of our knowledge, there is no comprehensive framework that incorporates the foundations of haptic perception and is suitable for the whole variety of haptic feedback systems in virtual reality.

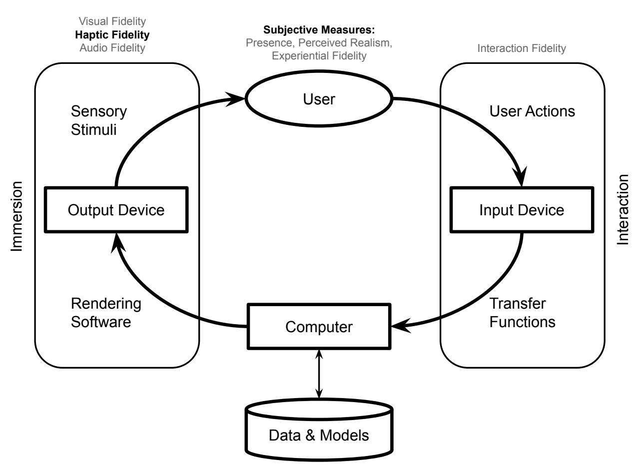

Figure 2: Human-VE interaction loop (first introduced by Bowman and McMahan [9]) with examples for objective measures: Visual Fidelity [9], Haptic Fidelity (presented in this paper), Audio Fidelity, Interaction Fidelity [51] and examples for subjective measures: Experiential Fidelity [2, 44], Presence and Realism [63, 69, 80].

Haptic feedback for VR is created as a response to an interaction with the system. A software then calculates the feedback controlling an output device which acts on the human body and creates sensory stimuli as shown in Figure 2. The user integrates all sensory stimuli into a comprehensive perception of the (virtual or real) world. The resulting user experience is highly subjective and depends on the context, the user's state of mind and past experiences [42]. While haptic feedback is strongly connected to the interaction and the user experience, it is primarily dependent on the output technology and human perception. Therefore it is connected to the concept of immersion describing the potential of a system to enable an elevated user experiences based on the system's rendering software and display technology. It refers to the objective level of sensory fidelity a VR system provides [68]. Other frameworks already rely on the definition of immersion as an objective measure to assess the fidelity of VR systems, such as the visual fidelity [9]. The fidelity of a system describes the quality of being accurate in its output. For haptic feedback "accurate" refers to the capability to produce realistic feedback which is consistent with what users have learned and thus expect from the real world. To assess haptic feedback systems regarding their potential to create realistic experiences, the objective level of sensory fidelity for the haptics must be considered.

In this paper we present the Haptic Fidelity Framework which can be used to assess haptic feedback systems in two dimensions: *Haptic Fidelity* describing the sensory fidelity and the resulting capability to produce realistic or abstract feedback relative to the intent of the system, and *Versatility* representing how specific the haptic feedback is for the particular use case. We validate our framework by applying it to 154 haptic feedback conditions of 38 research papers and compare the *Haptic Fidelity* score to the users' perceived realism. We contribute a comprehensive framework to qualitatively assess all types of haptic feedback systems for VR. It provides researchers and designers of haptic feedback systems with the ability to **anticipate** the fidelity and versatility of a system's feedback, **hypothesize** evaluation results, **compare** different systems or their variations, **decide** which solution best fits a use case, and **understand** the influencing factors of haptic feedback. The framework enables a deeper understanding of haptic feedback and its underlying concepts that can go beyond the application in the context of VR. We provide detailed examples on how to apply the framework in analyzing systems as well as five applications of how researchers and designers can employ the framework in their work with haptic feedback systems. By validating the framework with a wide variety of existing feedback modalities from research, we provide evidence for its usefulness in research and design.

2 RELATED WORK

Haptic feedback has been shown to have an added value for the user experience in general [48] and for immersive VEs specifically [28, 34]. As a result, researchers have developed frameworks to analyze and structure haptic feedback systems. Seifi et al. [65] provide a taxonomy to structure haptic feedback devices based on physical and utility device attributes. Haptic devices were also organized by attributes, categories, and similarities utilizing experts' mental models [66].

Several works propose performance metrics based on physical measures for the design [36] and evaluation of haptic feedback systems [23, 59]. Samur [59] proposes performance metrics based on physical measures for unpowered, powered, and controlled systems (e.g., kinematics, actuation, or impedance) as well as a test bed consisting of six experiments for psycho physical evaluations of haptic feedback systems. While physical metrics such as motion range, peak force, or inertia [23] provide objective measures, each of them is only applicable to a certain type or category of feedback devices and does not provide well defined measures for the whole spectrum of haptic feedback devices.

The user experience of haptic feedback is covered by several frameworks. Hamam et al. [21] introduce a model to capture the quality of experience that integrates both quality of service metrics, e.g., response time and user experience measures. Kim and Schneider [38] define the term "haptic experience" to capture the unique impact of haptic feedback on user experience with a focus on vibrotactile feedback. They propose design parameters, usability requirements and experiential dimensions as well as an initial scale to measure vibrotactile experiences [61]. Furthermore, the language to describe and communicate about haptic feedback has been examined. In a study by Obrist et al. [54], 14 categories of experiential vocabulary have been identified to describe the user experience of vibrotactile feedback. Targeting a wider spectrum of haptic feedback modalities, Schneider et al. [62] identified three themes: the multisensory nature of haptic experiences, a map of the collaborative ecosystem, and the cultural context of haptics for the design of haptic experiences. The survey from Bouzbib et al. [8] investigates the close relationship of interactions and haptic feedback for a wide variety of feedback solutions and propose two dimensions: the solution's degree of physicality and degree of actuation.

While the goal of an improved user experience by adding haptic feedback is clear, the effects thereof are more complicated. Berger et al. [4] investigated the uncanny valley of haptics showing that haptic feedback can reduce subjective realism if is incongruent with other sensory stimuli. Measuring the effects of haptic feedback on user experience with standardized questionnaires is still challenging. Although some questionnaires integrate optional questions related to haptic feedback, e.g., the Presence Questionnaire by Witmer and Singer [80], or the haptics addition [6] for the User Experience Questionnaire (UEQ) [41], they often do not cover the variety of haptic feedback methods and only cover specific aspects of the user experience.

In contrast to the focus on the subjective user experience, the effects of immersion as an objective measure for the technology [68] enabling a heightened user experience have also shown to be valuable for the analysis of VR applications. Bowman and McMahan [9] analyze the effect of visual fidelity and its hardware and software factors, e.g., field of view, display resolution, and frame rate, relating them to immersion benefits and the application effectiveness in creating a realistic and believable VE. McMahan et al. [50] have also evaluated the effects of display fidelity and interaction fidelity [51] and suggest a framework to analyze the realism and naturalness of interaction. They found that both display and interaction fidelity significantly affect performance and subjective measures of presence, engagement, and usability. Furthermore, Lindquist et al. [45] studied the effect of audio fidelity in VR indicating that ambient sound and sound realism increase perceived realism. In a meta-analysis, Cummings and Bailenson [13] showed that factors of technological immersion have a medium-sized effect on presence and that aspects of user-tracking, stereoscopic visuals, and wider fields of view are significantly more impactful than others.

The existing literature shows that several frameworks have been proposed focusing on physical measures or the user experience of VEs with haptic feedback. While immersion and its objective measures have been shown to give valuable insight to the underlying effects of user experience and constitute a predictor of presence or perceived realism, to the best of our knowledge there is no comprehensive framework integrating perceptual and technological measures of immersion covering the whole variety of haptic feedback systems.

3 HAPTIC PERCEPTION

Humans perceive haptics through their cutaneous and kinesthetic systems enabling the perception of material characteristics of surfaces and objects as well as position and movement of their own body. Each of these systems relies on various receptors, which are distributed across the skin surface for the cutaneous system, and the muscles and the tendons for the kinesthetic system.

The cutaneous system is concerned with the perception of tactile information based on four different kinds of mechanoreceptors and general free nerve endings. They provide information about skin stretch and sustained pressure (Ruffini corpuscles), pressure changes and vibrations (Pacinian corpuscles), shape and texture changes (Meissner's corpuscles), pressure, position, and deep static touch features (Merkel nerve endings), as well as touch, pressure, and stretch (free nerve endings) [18, 43]. In addition, thermoreceptors provide information about heat and cold. The receptor density differs on the human body which leads to variations in the spatial resolution of tactile perception. The density was evaluated through two-point touch distance and point localization threshold experiments [43].

The kinesthetic perception originates from mechanoreceptors in the muscles and joints, which provide information about changes in muscle length and velocity (primary and secondary muscle spindles), muscle tension (Golgi tendon organs) and joint extension or flexion (joint receptors) [32, 43]. These signals build our awareness of where our limbs are in space, how they move, and of mechanical properties of objects (e.g., weight, compliance).

All cutaneous and kinesthetic inputs are combined and weighted into a comprehensive haptic perception of the world. The combination of these stimuli enables the perception of haptic features, like the volume and global shape of larger objects, which go beyond low-level tactile properties.

4 THE FRAMEWORK

In this work, we develop a comprehensive framework that incorporates the full spectrum of haptic feedback systems independent of the used technology or addressed body parts. Our goal was to identify a set of criteria that systematically assesses haptic feedback systems. While the user experience of such systems is extremely important for VR applications, it is also highly subjective making it challenging to find a consistent understanding of the underlying processes. Therefore, we aim for more objective criteria that rely on the foundations of perceptual psychology and properties of the technology. As these criteria represent measures of immersion, they represent indicators that can influence the user experience (e.g., perceived realism) and should be considered when evaluating haptic systems. While physical measures also provide objective criteria, they are only applicable to certain feedback devices, e.g., force is only a valid measure for active devices with a motor but not for passive haptic props. In order to cover the full spectrum of possible feedback devices we integrate a layer of abstraction by assessing the match to reality for the particular use case of a system. The framework consists of two dimensions. The *Haptic Fidelity* dimension provides 14 criteria for assessing how abstract or realistic a system can produce haptic stimuli. A second *Versatility* dimension describes how specific the haptic feedback is for the particular use case. The two dimensions cover the trade-off between very realistic feedback for a specific scenario, and creating feedback that can be applied to many different scenarios but is more abstract. The target users of our framework are researchers, developers, and designers. It provides them with means to anticipate, hypothesize, compare, decide, and understand haptic feedback devices and their fidelity as well as versatility.

4.1 Method

For the development of the framework, we used an iterative process over the course of several months to define the framework and identify its factors. We started with an inductive approach by collecting relevant factors that influence the quality of haptic feedback. In addition, we deductively identified three important categories based on the definition of the human-VE interaction loop: *Human Sensing*, *(Display) Hardware*, and *Rendering Software*. To find relevant factors for the *Sensing* category, we conducted a comprehensive literature review on how humans sense haptics, presented in section 3, and studied findings from perceptual psychology [18, 32, 35, 43]. For the *Hardware* and *Software* categories we examined common technology metrics for haptic devices [23] and general output devices [50] that would be relevant for rendering haptic feedback. In the iterative process, the team of authors continuously proposed new or adapted existing factors and then checked if they can accurately represent a variety of haptic feedback systems. We selected nine papers [5, 14, 15, 19, 46, 60, 83, 84, 86] with diverse haptic feedback modalities as references for repeated evaluations of the factors. Our assessment and adaption of factors considered both the conformance to concrete systems and the general applicability to a wide variety of different systems. The evaluation of factors was conducted with a critical mindset to challenge if they accurately and fully cover the whole range of feedback systems. After several iterations, the process resulted in a set of 14 factors.

We then conducted a workshop with seven experts in VR and haptic feedback research. The experts either had designed and built haptic feedback systems themselves or had applied them in their research. Their expertise ranged from material aspects and tangibles (14 years), physical objects in VR and actuated devices (6 years), feedback for medical applications (6 years), interaction techniques in VR (5 years), haptic feedback for psychotherapy in VR (3 years), sports and exergames in VR (3 years) to everyday materials in VR (4 years). During the workshop, the experts were asked to intuitively rate each of the feedback systems from the above-mentioned papers and then to apply the factors to the systems. In a discussion round we asked the experts how well the factors represented the systems, how well the factors could be applied to all systems and if some aspects of the systems were not covered. We received positive feedback for the presented 14 factors, but five experts mentioned that they were missing factors that describe how versatile a system is. They wished for factors that described how generic a feedback system is to be used for different applications. As these aspects do not describe qualities of the haptic feedback but rather how the system can be used, we introduced a second orthogonal dimension to the framework integrating this aspect.

4.2 Haptic Fidelity

In the following, we define *Haptic Fidelity* and introduce the 14 independent factors characterizing this dimension. An overview is shown in Table 1.

4.2.1 Definition. *Haptic Fidelity* describes an objective measure for the qualities regarding the realism of a haptic rendering system. It takes into account how the haptics are rendered and which haptic receptors are addressed but does not describe how a user will experience the haptics. It provides a measure of how realistic the system can reproduce a haptic experience through its rendering mechanisms, thus the potential for a realistic perception from the user. A system with high *Haptic Fidelity* should provide realistic rendering mechanisms that address the same haptic receptors (e.g., skin stretch, pressure, or force) in the same intensity as in the real world. In addition, no noise or confounding factors should interfere with the haptic perception. As the actual haptic quality of the system, which is how a user will experience the system, is not directly linked to how the haptics are rendered, a lower *Haptic Fidelity* is not of inferior quality but displays a different kind of haptic quality. We refer to this quality as "abstract" as it stands in contrast to the realistic rendering mechanisms of a system with high *Haptic Fidelity*. A system with an abstract quality might only address a small number or a single type of haptic receptors. It might also facilitate a particular haptic stimuli to convey the perception of other haptic impressions (e.g., use vibration to simulate a force). In addition, the system might have limiting factors such as imprecision or noise.

4.2.2 Haptic Fidelity Factors. This dimension incorporates 14 independent factors from Table 1 to assess *Haptic Fidelity*. They are divided into three categories: Sensing, Hardware, and Software. The factors are further differentiated between *foundational factors* (F) that describe the features of a system and the value they provide, and *limiting factors* (L) that comprise factors negatively impacting the perception. The set of *foundational factors* (such as *Magnitude* or *Sensory Integrity*) represent the added value of the system. *Limiting factors* on the other hand can merely diminish this value. If a limitation is only minor or does not apply to a system at all, the overall value of the system does not change, while major limitations can drastically impair the whole system. We consider the latency of a system, for example, as a *limiting factor*, because it can only have a negative impact though never enhance a system. Factors that do not apply to every feedback system are also included in the *limiting factors* as they do not impact the value of a system if they are not applicable. Combining all individual factors into one overall

Table 1: Overview of the three categories *Sensing*, *Hardware* and *Software* with the 14 individual factors of the *Haptic Fidelity* dimension including indication for foundational (F) and limiting (L) factors and brief descriptions.

Haptic Fidelity		
Sensing		
Body Location	F	The degree to which the same location(s) on the body or body parts of the user are involved.
Body Area	F	The degree to which the same extent of body surface of the user is involved.
Stimuli	F	The degree to which the same haptic receptors of the user are involved.
Magnitude	F	The degree to which the same intensity and variation of stimuli are involved.
Sensory Integrity	F	The degree to which the haptic stimuli and stimuli of other modalities match regarding the intent of the system.
Dependency	L	The degree to which the absence of different dependent haptic stimuli that are usually perceived together in reality has an impact on the haptic perception of the system.
Distinguishability	L	The degree to which the distinguishability of different physical properties rendered by the system has an impact on the haptic perception of the system.
Hardware		
Degrees of Freedom	F	The degree to which the system can provide haptic feedback with the same degrees of freedom.
Hardware Precision	F	The degree of detail to which the hardware is able to create the intended haptic feedback.
Hardware Latency	L	The degree to which the hardware latency has an impact on the haptic perception of the system.
Side effects	L	The degree to which the system creates unintended haptic stimuli.
Constraints	L	The degree to which the system constrains the user’s movement other than in the intended way.
Software		
Software Precision	F	The degree of detail to which the software is able to simulate the intended haptic feedback.
Software Latency	L	The degree to which the software latency has an impact on the haptic perception of the system.

score, the *Haptic Fidelity* dimension provides a single measure for haptic rendering systems that describes how abstract or realistic the system can potentially provide haptic feedback to a user for a particular use case.

In order to cover the whole variety of haptic feedback devices, the factors of this dimension rely on objective measures but are assessed on a more abstract level. While physical measures can only be applied to certain aspects of haptic feedback, the individual factors represent higher-level concepts that can include multiple physical measures of the same kind, e.g., the *Magnitude* factor can describe the strength of a force, a temperature difference, or the amplitude of a vibration. Further, the use case in which a feedback system is applied plays a central role for the assessment of fidelity. To assess whether a system provides realistic feedback, the same physical measures might be compared, but the order of magnitude could be completely different. A small force to the fingertip might be considered realistic to simulate the touch of a soft material but the same force would not be considered realistic to simulate weightlifting. In addition, the impact of limiting factors might be different depending on the use case. The impact of latency might be higher for simulating force feedback when playing tennis than for simulating the heat from a campfire. Therefore, the factors of the *Haptic Fidelity* dimension can only be evaluated in relation to what is intended to be conveyed by the system. If a system is designed to simulate the feedback of punches from boxing, it should only be evaluated how realistic these punches can be represented but not how realistic the system can, for example, represent touching flowers. Therefore, *Haptic Fidelity* and its factors are relative scales that capture the qualitative assessment of how realistic or abstract the feedback is for a particular use case.

In the following, the individual factors are described in detail. The descriptions contain the phrase “The degree to which the same ...” where “the same” refers to how or where the intended haptics would be perceived in reality. Each foundational factor is rated between "no match at all" and "complete match" with reality while limiting factors are rated between "no impact" to "very strong impact" on the perception. The following factors are part of the **Sensing** category about the human capabilities to sense haptic stimuli.

Body Location (F) *The degree to which the same location(s) on the body or body parts of the user are involved.*
This factor describes where on the user’s body the haptic feedback is created by the system and to what extent this is in line with where one would perceive the stimulus in the natural occurrence of the intended haptics. This scale is grounded in the human ability to localize a haptic stimulus on the body (bodily localization [43]).

Example: Using EMS on the upper and lower arm to simulate lifting a virtual box, like the system by Lopes et al. [47] does, would get a medium-high score as it correctly involves the arms to simulate the weight of the box, but does not give feedback on the fingers and hands where the box is touched.

Body Area (F) *The degree to which the same extent of body surface of the user is involved.*
This factor describes how well the system provides haptic feedback to the same extent of area on the user’s body where one would get feedback in the natural occurrence of the intended haptics. This scale is grounded in the spatial resolution of haptic receptors in the human body and the ability to relate stimuli to each other, forming a consistent sensory impression [43]. The differences in density of haptic receptors should be considered for this factor. Hence, a system that intends to convey haptics to the fingertips should match the area more precisely than a system affecting the upper arm.

Example: Simulating the haptic feedback of a boxing punch with a small, actuated plate on the forearm of a user, like the Impacto system [46] does, involves a significantly smaller area than a boxing glove would impact. Therefore, such a system would get a medium-low score.

Stimuli (F) *The degree to which the same haptic receptors of the user are involved.*
This factor describes how well the system stimulates the same haptic receptors as they would be stimulated in the natural occurrence of the intended haptics. It is grounded in the existence of different haptic receptors in the human body as outlined in section 2. Each

kind of receptor responds to different forms of stimuli, making it possible to perceive and differentiate a variety of haptic properties [43]. While each kind of receptor responds to specific low-level stimuli, perceptual psychology classified haptic stimuli into higher-level perceptions that can be distinguished by humans. To rate this factor without deeper knowledge in perceptual psychology, we provide Table 2 that relates the perceivable haptic stimuli with physical properties that can be rendered by haptic feedback devices.

Example: Using the vibration of a VR controller to give feedback for the contact force of virtual walls, as it is done in one of the conditions by Boldt et al. [5], involves completely different haptic receptors leading to a low score.

Magnitude (F) *The degree to which the same intensity and variation of stimuli are involved.*
This factor describes how well the system creates the same strength (e.g., same force) or variation (e.g., same texture) of haptic stimuli compared to the natural occurrence of the intended haptics. The scale is grounded in the ability of human haptic receptors to perceive different variations of stimuli. When rating this scale, the just noticeable difference in sensations from a haptic system should be considered [33].

Example: Simulating the haptic feedback of a boxing punch, like the Impacto system [46] does with EMS and a small, actuated plate on the forearm, can only represent the force to a medium degree and the pressure applied to the forearm to a low degree. Therefore, such a system would get a medium-low score.

Sensory Integrity (F) *The degree to which the haptic stimuli and stimuli of other modalities match regarding the intent of the system.*
This factor describes to what extent the haptic stimuli match with the perception of the other senses that are also addressed by the system and if this match is in line with the intent. It is based on the human ability to integrate all senses into a consistent perception of the world. The senses are weighted differently for this integration; especially vision has been found to be weighted more strongly [43]. This visual dominance effect [24] leads to the possibility that the visual perception can influence how the haptics are perceived.

Example: A physical sandbox with a VR visualization, e.g., as by Fröhlich et al. [15], can display water evoking the expectation that the haptic perception will be consistent with it and feel like water, but the user will only perceive the haptics of sand. This can be rated with a medium degree of integrity as it does not match to full extent but is also better than perceiving a solid surface or nothing at all.

Dependency (L) *The degree to which the absence of different dependent haptic stimuli that are usually perceived together in reality has an impact on the haptic perception of the system.*
This factor describes if the system creates different haptic stimuli that are usually perceived together in nature, e.g., weight together with weight distribution when lifting an object. The fact that these dependent haptic stimuli are naturally perceived together create the expectation to always perceive dependent haptic stimuli together. Therefore, this factor is based on the integration of different haptic stimuli and the learned expectations which haptic stimuli are generally perceived together. This factor is a limiting factor because not all haptic stimuli have other dependent stimuli.

Example: A force feedback glove can be used to render the weight, contact force, volume and shape of objects that can be touched and lifted. But it does not provide dependent haptic stimuli like the texture or temperature of the object, which would be perceivable when touching an object in reality. Therefore, it has some limitations and a medium-low impact on the haptic perception can be assumed.

Distinguishability (L) *The degree to which the distinguishability of different physical properties rendered by the system has an impact on the haptic perception of the system.*
This factor describes if different physical properties that are intended to be conveyed by the system can be distinguished by either targeting different haptic receptors shown in Table 2, or through spatial or temporal separation. Different haptic receptors and the integration of different haptic stimuli makes it possible to distinguish a variety of haptic properties. While in nature each object has individual haptic properties, haptic feedback systems are sometimes only capable of providing a limited number of haptic stimuli. Remapping haptic stimuli to represent other physical properties is often used in these cases, e.g., using vibration to represent the contact force of an object. This might work well with a distinct mapping where users can clearly identify and learn the remapping, but can lead to confusion and unrealistic sensations from ambiguous mappings. This factor is a limiting factor because not all systems intend to render multiple physical properties or use any kind of remapping.

Example: A system that uses vibration to render texture and contact force of an object when touching it would make it challenging to distinguish which of the two physical properties is currently rendered or varied. Therefore, such a system would get a high rating due to its limitations.

The following factors are part of the **Hardware** category about the devices that are used to create the haptic feedback.

Degrees of Freedom (F) *The degree to which the system can provide haptic feedback with the same degrees of freedom.*
This factor describes if the hardware of the system provides at least the same number of degrees of freedom (DoF) as in the natural occurrence of the intended haptics. The system can have more degrees of freedom than they require making the system more versatile. Naturally, objects that can be freely moved and rotated have 6 DoF while slide doors would only have 1 DoF and walls none. This factor is based on the fact that haptics are naturally present in multiple dimensions which must be represented by technical solutions. If the system provides a certain number of DoF but the user's range of motion is limited within these through the system, it is not considered in this factor but part of the factor *Constraints* below.

Example: The Aero-Plane system [31] is a custom controller with two vertical propellers meant to simulate the forces of a ball rolling on a plane, or the motion of food in a pan. The system offers two DoF through the actuation of the propellers creating forces in the left/right and up/down directions. To properly simulate the intended scenarios, a third DoF would be necessary to also create forces in the front/back direction. Therefore, the system receives a medium-high score.

Hardware Precision (F) *The degree of detail to which the hardware is able to create the intended haptic feedback.*
This factor describes to what extent the system can reproduce the detail of haptic feedback compared to the natural occurrence of

Table 2: Mapping of perceivable haptic stimuli (listed vertically on the left) and physical properties (listed horizontally above) of objects and surfaces. The haptic stimuli are based on perceptual psychology literature [43] classifying low-level stimuli into higher-level perceptions that can be distinguished by humans. We mapped the relationships of these haptic stimuli to physical properties that might be rendered by haptic feedback systems based on the involvement of the different haptic receptors. Forces are classified as either body forces (generated through the interaction of physical bodies with mass, force, velocity, etc. or force fields such as gravity) or contact forces (produced by direct physical contact) [52]. We distinguish four categories of involvement:
🟩 **This haptic stimulus is always involved in the perception of this physical property;**
🟧 **This haptic stimulus is always involved in the perception of this physical property when the object or body is in motion;**
🟨 **This haptic stimulus is possibly involved in the perception of this physical property depending on how the object or surface is touched;**
⬜ **This haptic stimulus is normally not involved in the perception of this physical property.**

physical properties / haptic stimuli	weight (distribution)	volume	shape	texture	compliance	friction	temperature	contact force	body force
skin stretch	🟨			🟨	🟨	🟩		🟨	🟨
sustained pressure	🟩	🟩		🟨		🟨		🟨	🟨
pressure changes	🟧		🟧	🟨	🟩	🟨			🟧
vibration				🟨		🟨			
shapes / edges		🟨	🟩	🟨					
texture				🟩					
temperature							🟩		
proprioception		🟩	🟨		🟨			🟨	🟨
constant force	🟨	🟩				🟨		🟩	🟨
force changes	🟧		🟧		🟩	🟨			🟧

the intended haptics. It is based on the necessity of mechanical components with varying and unavoidably finite accuracy. This can include the resolution of building blocks or the detail of object resemblance. Related aspects that can influence the precision, e.g., calibration imprecision or joint tolerance, should also be considered for this factor.

Example: The precision of a pin-based system to render the shape of objects is dependent on the number and size of the individual pins. The PoCoPo system [84] uses a small number of 1 cm wide pins which is a low resolution compared to the sensory resolution of the hand. It would therefore get a medium-low score. A study by Muender et al. [53] compares three types of passive haptic props with different degrees of detail. The differences in prop detail can be expressed in this factor.

Hardware Latency (L) *The degree to which the hardware latency has an impact on the haptic perception of the system.*
This factor describes the influence of the hardware latency on the haptic perception. It is based on the fact that technical solutions often require time to transmit signals and mechanically change their states. While in nature haptics are almost always perceived immediately to an action, the latency of haptic feedback systems can lead to a delay in the haptic perception and therefore result in unrealistic sensations. The time until a delay is noticed and the influence of delay on the perception depends on the kind of stimuli and situation [30]. Delays over 25 ms to 100 ms are commonly reported to be noticeable and have an impact on performance. This is a limiting factor because latency can only have a negative impact on the haptic perception and will never enhance a system.

Example: The Shifty system [86] actuates a weight up and down in a tube to simulate different weight distributions, which takes up to 2.8 s. Since this latency is not constantly noticeable but only when a different virtual object is picked up, and since it is mitigated by adjusting the weight already before grasping, the system would get a medium score.

Side Effects (L) *The degree to which the system creates unintended haptic stimuli.*
This factor describes how the haptic perception is influenced by any side effects that the hardware of the system creates. This can include the vibration of motors, pain from EMS, or forces from moving parts. It is based on the fact that technical devices can produce unintended haptic stimuli which may lead to distraction, irritation, and unrealistic sensations. This is a limiting factor because side effects can only have a negative impact on the haptic perception and never enhance a system.

Example: EMS systems, such as by Lopes et al. [47], can cause unpleasant traction, tickle, or even pain leading to a medium score. Other systems that have actuated parts, as the Shifty system [86], will create unintended counter forces and inertia from the device adjusting, leading to a low score.

Constraints (L) *The degree to which the system constrains the user's movement other than in the intended way.*
This factor describes how the haptic perception is influenced by constraints that the hardware imposes on the user's range of motion. This could be caused by joint limits, wire length or colliding parts of the hardware. It does not consider if the system intentionally limits the user's range of motion to render haptics. This factor is based on the fact that technical solutions might restrict the user's freedom of movement because of the system design or mechanical components such as wearables or wires. This is a limiting factor

because constraints can only have a negative impact on the haptic perception and will never enhance a system.

Example: An exoskeleton or robotic arm that limits the range of motion of the user's arms due to its joint limits or world-grounding, as it is the case in [58], would get a medium score.

The following factors are part of the **Software** category about the software that is used to create the haptic feedback.

Software Precision (F) *The degree of detail to which the software is able to simulate the intended haptic feedback.*
This factor describes how accurately the software can calculate the haptic feedback to be rendered. This can include how accurate colliders represent the shape of an objects or how accurate a physical simulation can calculate the compliance of an object. It is based on the fact that the feedback has to be calculated by software before it can be displayed by hardware.

Example: If an exoskeleton is used to render the contact force of an object but the collider to represent the object uses an inaccurate low-resolution mesh, the hardware can at most render the haptics with this low resolution. Depending on how low this resolution is, the system would have a low or medium-low score.

Software Latency (L) *The degree to which the software latency has an impact on the haptic perception of the system.*
This factor describes the influence that the software latency has on the haptic perception. It is based on the fact that the necessary calculations take time and may cause a noticeable delay. The same threshold for noticeable delays as in *Hardware Latency* apply for this factor. This is a limiting factor because the presence of latency can only have a negative impact on the haptic perception and will never enhance a system.

Example: A system that takes 500 ms to simulate the compliance of an object creates a noticeable delay. A latency of 500 ms can be interpreted as a medium impact on the haptic perception and therefore would get a medium score.

4.2.3 Scoring. The individual factors of the *Haptic Fidelity* dimension can give designers and researchers insight into the importance of certain aspects of haptic feedback in VR or the origin of limitations. Yet, to structure the qualitative assessments of individual factors and effectively compare different systems that have the same or similar use cases, a single comprising score representing the complete *Haptic Fidelity* of a system is required.

$$\underbrace{\frac{\sum_0^{N_F} X_F}{N_F}}_{\text{mean of foundational factors}} \cdot \underbrace{e^{-0.0027\cdot(\underbrace{\sum_0^{N_L} X_L^2}_{\text{sum of squared limiting factors}})^2}}_{\text{exponential function for the influence of limiting factors on the value of a system}}$$

Figure 3: Equation to calculate a single score for *Haptic Fidelity*, with N_F for the number of foundational factors, X_F for the respective rating of the foundational factors, N_L for the number of limiting factors and X_L for the respective rating of the limiting factor.

To build an overall score, all factors first have to be evaluated in terms of actual numbers. We propose to evaluate each factor on a 5-point Likert-scale (0–4), as it offers a good trade-off between having enough options to differentiate systems[1] but still having distinct differences between ratings to enable clear decisions which rating represents a system best. To calculate a single score for each dimension that properly represents the systems on the respective scale the foundational factors (F) will be averaged as they all represent an added value to the system. Limiting factors (L) on the other hand represent aspects that negatively impact the system and consequently have to lower the overall score. Therefore, the scales for limiting factors must be inverted (0 – no limitation; 4 – strong limitation). In addition, a high limiting factor can drastically influence the value of a system, e.g., if the software latency is 5 seconds, it does not matter how fast or accurate the hardware is or if the right receptors are targeted, the latency still limits the whole systems. To reflect this in the score we propose to square the ratings of limiting factors, giving them increased influence on the final score. To combine the scores of foundational and limiting factors our goal is to calculate a value between 0 and 1 that can be multiplied with the foundational score where 1 implies no limitations leaving the foundational score as is and 0 representing strong limitation completely nullifying the value of the system. To develop a suitable function that results in a fitting overall score, we used an iterative approach where we tested and adapted several different functions and aimed for a good match with the assessments of the experts from the workshop. This approach resulted in an exponential function of the form $e^{-\alpha * x^2}$ to transform the sum of all squared limiting factors into the desired range. This function satisfies two requirements: First, $f(0) = 1$ with 0 being the sum of all limiting factors representing no limitation at all. Second, the fact that one high limiting factor can already drastically lower the value of a system is represented in the exponential function having a quick drop off. For multiple high limiting factors, the multiplication factor approaches zero representing the strong negative impact. To determine the α-factor for the exponential function we use the rational that if one limiting factor receives a maximum score (4) the foundational score should be reduced by half, which was based on a good fit to the assessments of the experts. As a result we use the formula shown in Figure 3 to calculate the final score for *Haptic Fidelity*.

4.3 Versatility

The *Versatility* dimension of the framework describes a measure on how specific a system is in providing haptic feedback for a particular application. A similar definition of versatility as an important attribute of haptic systems was given by Seifi et al. [66]. This dimension exists orthogonal to the *Haptic Fidelity* dimension as it represents the trade-off between highly realistic but application-specific and more abstract but widely applicable feedback. Systems that provide abstract feedback are naturally more widely applicable for different application scenarios as the feedback can be repurposed to represent any kind of other more specific feedback (e.g., vibration feedback is used to represent contact force or weight).

[1]Three options as used for the interaction fidelity [49] do not properly capture the differences of certain factors like the *Body Area*.

Realistic feedback, on the other hand, can be achieved by designing systems that are custom-made for a particular application. Only addressing receptors at the exact body position necessary for the intended application makes these systems extremely specific to this scenario. Placing feedback systems in the space of these two dimensions should give researchers and designers a better understanding on how the realism of feedback is connected to the possible use cases and how more abstract feedback can be applied to different applications. While *Haptic Fidelity* was assessed by individual factors, the *Versatility* dimension provides a single factor rating haptic feedback systems on a scale from specific to generic. How a system is rated on this scale does not have any implication for the overall quality of a system but rather represents how versatile it can be used.

We propose to assess *Versatility* on a 5-point Likert-scale (0–4) with 0 representing systems that are extremely specific to the intended application and 4 representing systems that are generic in its feedback. As the specificity of a system is not based on objective measures to the same degree as the factors from *Haptic Fidelity* are, we provide categories describing the five levels of this scale. The examples provided for the following categories are illustrated in Figure 4.

0 The systems feedback is specific for one particular variation of a use case (e.g., for a particular climbing wall, where other variations of haptics cannot be rendered [64]).
1 The systems feedback is specific for a particular use case (e.g., boxing [46]) and supports different variations (e.g., the system could provide feedback for other variations like different boxing fights or even other kinds of martial arts).
2 The systems feedback is quite specific for a group of use cases to which the particular application belongs to (e.g., all scenarios with small handheld objects [39]).
3 The systems feedback is unspecific for a particular use case and generic to a larger group of applications (e.g., a force feedback glove [70] or an exoskeleton).
4 The systems feedback is completely generic and not specific for almost any application (e.g., vibration from VR controller as feedback [57]).

These categories provide the means to congruently rate the versatility of haptic feedback systems and generate a score for the *Versatility* dimension. Similar to the *Haptic Fidelity* this dimension has to be rated relative to the intended application of the haptic feedback. This is necessary to generate valid ratings that are consistent between the two dimensions. A standard VR controller with vibration would normally be considered very generic in its feedback. But if the scenario is to render the haptic of a vibrating phone, for example, it has to be considered as more specific for this particular use case.

4.4 Framework Application

Our framework provides the means for a structured and informed assessment of haptic feedback devices that is based on factors, which are evaluated qualitatively in the context of a specific use case. The factors allow for a detailed assessment that covers all relevant aspects of a system. The framework forms the basis for consistent and comparable assessments as always the same aspects are evaluated and none are missed. It also provides a defined vocabulary for a more precise communication of the analysis and results.

The framework is intended to give qualitative insight into the underlying properties of haptic feedback systems. The individual factors provide the means to think about these underlying concepts and support formalizing them in a quantitative way, i.e., with a score. The score is intended as a tool to structure the inspected qualitative aspects. An assessment of a system should not be made in isolation but should always consider how the same system would be rated when certain aspects were changed or in relation to similar systems that can be applied to the same use case. The individual factors have to be evaluated in relation to the intended use case of the system and therefore provide relative insights. For assessments of different systems or system variations to be comparable, they have to be made on the same basis of assessment framed by the particular use case and by similar systems that are employed as reference.

We intend the framework to be used by individuals or groups of researchers and designers to qualitatively assess feedback systems and make relative comparisons within the same use case or similar ones. In the following, we will present five applications of the framework to illustrate how it can be used. Each application is aimed at a certain user group. The required expertise to apply the framework may vary depending on the application but a general overview of different haptic devices that can be used as reference is advised. A basic knowledge can be sufficient when using the framework to understand and learn about haptics while precise anticipation of evaluation results might require a wider overview of feedback possibilities and an understanding of how haptic feedback is perceived. However, even if not all details are taken into consideration, the framework can still provide valuable insights into the qualities of a system by its structured approach.

4.4.1 How to Use the Framework. The following five applications illustrate how the framework can be used in the work of researchers and designers.

Anticipate: Researchers and designers can apply the framework when designing haptic feedback devices or prototypes to anticipate the realism of feedback and versatility of the system. The framework can be used iteratively from early technical concepts to the final building phase to provide indication on the outcome. The individual factors can further provide guidance on what can be adjusted to result in the desired feedback.

Hypothesize: Researchers can use the framework to formulate reasoned hypotheses for their evaluations of haptic feedback systems and discuss the findings based on the dimensions and factors from this framework.

Compare: Researchers and designers can apply the framework to compare device variants, e.g., [71], or different feedback devices for the same use case, e.g., [31, 85]. The framework can be used to identify similarities and differences between the devices. The factors of the framework can give insight where these differences are, how decisive they are, and what the underlying perceptual or

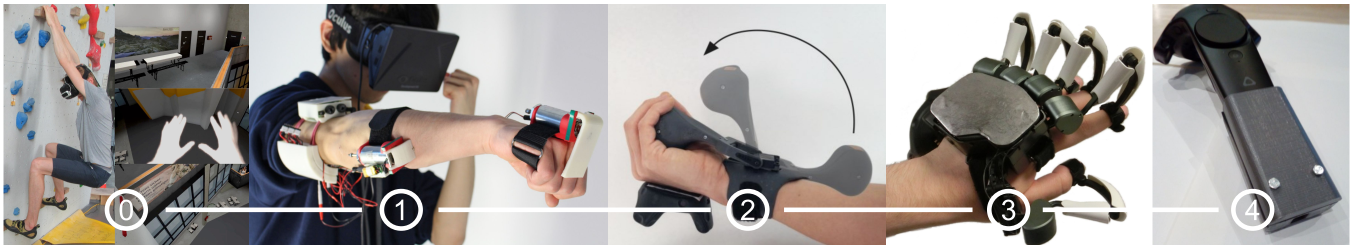

Figure 4: Examples for the five levels of specificity from the *Versatility* dimension, from (0) specific to (4) generic. (0) Schulz et al. [64]: climbing condition; (1) Lopes et al. [46]: EMS and solenoid condition; (2) Kovacs et al. [39]: catching condition; (3) Steed et al. [70]: free condition; (4) Ryge et al. [57]: high fidelity condition. Image copyrights from left to right ©Peter Schulz, ©Pedro Lopes, ©Robert Kovacs, ©Anthony Steed, ©Andreas Ryge.

technical reasons are.

Decide: Product designers can use the framework to make informed decisions which feedback device to select or develop for their specific use case. Researchers can also apply the framework to select appropriate feedback devices to best answer their research questions. The framework can help finding a suitable compromise of overall realism and wide applicability of a product or provide detailed information on the underlying factors to guide decisions.

Understand: The framework can be used to understand influencing factors on haptic feedback. In combination with existing literature, it facilitates a comprehensive understanding of haptic feedback that can inform future research and development. Researchers can use it to soundly interpret the results of evaluations. Further, educators can use it to teach about haptics and give students an overview of existing systems or approaches. Designers can apply the framework to understand why their product performs the way it does. Lastly, the vocabulary established in this framework can help experts express themselves accurately when exchanging with peers.

4.4.2 Example Application of the Framework. In the following, we provide an example describing in detail how different haptic feedback conditions from a research publication can be evaluated with our framework and how the assessments can be used to *Hypothesize* and *Compare* the conditions. In this section, we focus on reporting and motivating the scores for each factor, which are listed in Table 3. Further details on the procedure of applying the framework can be found in subsection 5.2. For comparison, we also provide a classification of ten haptic feedback systems into the two dimensions of the framework in Figure 5.

The paper "The Role of Physical Props in VR Climbing Environments" by Schulz et al. [64] presents a system to simulate the experience of climbing in a climbing gym. The paper has three conditions of which one is real climbing without a VR headset leaving two conditions that can be analyzed. The first condition (C) enables climbing by the means of standard VR controllers with vibration feedback while the second condition (W) enables climbing with hands and feet in VR on a real climbing wall providing passive haptics. The scores for all factors are listed in Table 3.

Table 3: Ratings of all factors for the two conditions of VR climbing by Schulz et al. [64]. C – condition with a standard VR controller; W – condition with a real passive-haptic climbing wall. The 14 factors (either foundational or limiting, see Table 1) result in the score for haptic fidelity (see Figure 3 for the calculation). The score for versatility is expressed on a single scale (see Figure 4).

Factor	C	W
Body Location	1	4
Body Area	2	4
Stimuli	1	4
Magnitude	0	4
Sensory Integrity	1	4
Dependency	3	0
Distinguishability	0	0
Degrees of Freedom	0	4
Hardware Precision	0	4
Hardware Latency	0	0
Side effects	0	0
Constraints	0	0
Software Precision	4	4
Software Latency	0	0
Haptic Fidelity	**0.9**	**4.0**
Versatility	**4**	**0**

For the *Body Location*, the standard VR controller (C) only provides feedback to the hands but not to the feet, arms, legs, shoulders, or chest that would also experience the forces when climbing. Condition (W), on the other hand, involves all these body parts. The *Body Area* of the hands and feet is involved in climbing on a real climbing wall (W), whereas (C) only involves the skin surface of the hands. The controller (C) provides vibrations as haptic *Stimuli*, which do not naturally occur in climbing, as well as texture, shape, and contact forces but no stimuli for pressure, skin stretch, or forces of the user's body weight (cf. Table 2 for a general overview on different haptic stimuli). The provided stimuli intensity does not match at all with climbing leading to a low score for *Magnitude*. In contrast, the real climbing wall (W) creates the correct *Stimuli* with the right *Magnitude*. Because of this there is also a good match with the visual feedback of the system creating a high value for *Sensory Integrity* (W), whereas the controller (C) only has a limited match with the visuals. The absence of important haptic stimuli for the body weight or pressure on the fingers in the controller condition (C) creates a noticeable limitation in *Dependency*. For both the *Degrees of Freedom* and *Hardware Precision*, the real climbing wall (W) receives high scores as real grab handles and precise tracking are used. The controller (C), on the other hand, cannot represent the intended haptics of climbing to any precision and the 1 DoF of vibration does not match with the required DoF. The *Hardware Latency* is imperceptibly low for both conditions and imposes no limitations. There are no *Side Effects* or *Constraints* in neither of the conditions. The paper does not explicitly report on how the software calculates the haptics, but it is reported that the Unity game engine is used. Thus, it can be assumed that standard colliders with a high *Software Precision* and low *Software Latency* are used. After scores for all 14 factors are identified, overall haptic fidelity scores can be calculated based on the formula given in Figure 3. In our example, this results in a haptic fidelity score of 0.9 for the controller condition (C) and a score of 4.0 for the wall condition (W). Regarding *Versatility*, the climbing wall (W) is extremely specific for its scenario and can also only create feedback for this particular variation of a climbing wall, which is assessed with a score of 0 (category 0 in Figure 4). The controller (C) is considered completely unspecific for the climbing scenario, and thus receives a score of 4 (category 4 in Figure 4). Figure 5 presents the classification of these two conditions on the two dimensions *Haptic Fidelity* and *Versatility* together with eight other research systems for comparison.

The authors of the paper could apply this analysis to support their hypothesis that presence is expected to be higher for users in condition W than in condition C. As perceived realism is one key aspect of presence, the result of more realistic feedback for condition W (4.0) compared to condition C (0.9) supports this hypothesis. Further, the authors could have used this analysis to discuss their results and argue that, for example, the *Magnitude* had a great impact on this result. Comparing the two conditions, it becomes clear that the condition C provides highly versatile feedback while the W condition is focused on realistic feedback for one particular use case.

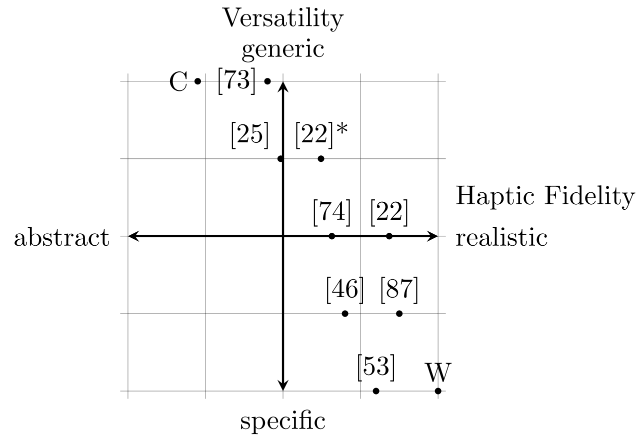

Figure 5: Exemplary classification of haptic feedback systems from research. C and W are the two conditions from VR climbing [64] in Table 3; "Does it feel real?" [53]: Lego condition; HapTwist [87]: Rubik's-Twist-based condition; Impacto [46]: high EMS and high solenoid condition; PuPoP [74]: Quidditch condition; Haptic Around [22]: hybrid condition; Haptic Around [22]*: controller-based condition; DextrES [25]: brake and piezo condition; DualVib [73]: chainsaw force & texture condition.

5 VALIDATION

In order for the framework to be of practical value for researchers and designers, so that they can compare haptic feedback systems and draw conclusions for their research and the design of new feedback methods, it is necessary to demonstrate that the framework is related to the user's actual perceived realism of a system. We formulate the following hypothesis describing the relation between the *Haptic Fidelity* dimension of the framework and the perceived realism to guide our validation procedure.

> **Hypothesis 1**: The haptic feedback of a system that has a high potential to produce realistic feedback, as described by the *Haptic Fidelity* score, will also be perceived as more realistic by users than a system that has a more abstract feedback potential.

The *Versatility* dimension was introduced to represent the potential trade-off between highly realistic but scenario-specific and more abstract but widely applicable feedback. We formulate a second hypothesis describing the resulting relation between the *Haptic Fidelity* and *Versatility*.

> **Hypothesis 2**: In haptic feedback systems, there is a trade-off between its *Haptic Fidelity* and its *Versatility*.

To validate these relationships, it is required to apply our framework to different haptic feedback modalities and evaluate the perceived realism of these modalities. However, it is not practical to evaluate the framework on some experiment as only a few haptic feedback modalities can be compared in a single user study. This does not represent the broad variety of different haptic feedback methods that should be covered by the framework and therefore would not give meaningful insights. Therefore, to validate our framework, we will build on the results of previous research papers which evaluated the perceived realism of different haptic feedback modalities in VR. By applying our framework to the feedback modalities of existing research and correlate the scores to the effect that the feedback modalities had on the perceived realism, we take the first step to demonstrate the validity of our framework.

5.1 Paper Selection

To find relevant papers that can be analyzed with our framework and give insight in the perceived realism, we conducted a literature review searching the ACM Digital Library and IEEE Xplore databases for papers related to the topics of VR and haptics. We selected papers that used VR headsets for the visual presentation and provided some form of haptic feedback. Papers that used other forms of presentation, e.g., augmented reality, 3D displays, or standard displays were excluded as we were especially interested in immersive technology where participants could not see the feedback systems. We further excluded papers published prior to 2000 in order for the technology, especially the VR headsets, to be comparable. As we were interested in user's perceived realism, we did not include technical papers without a user study in our selection. Further, papers in which no real haptic feedback is experienced by users, e.g., pseudo-haptics, or the main goal is not realistic feedback but rather guiding the attention, e.g., alerts, haptics for guidance or professional medical haptic devices were excluded from the selection. From this search we identified 160 Papers fitting our criteria. These papers were then further analyzed regarding whether they evaluated perceived realism in the user study by the means of standard or custom questionnaires. For standardized questionnaires we considered the realism sub-scales of the Witmer and Singer [80], IPQ [63] and SUS Presence [77] questionnaires. Only papers that had at least two conditions that compared different haptic feedback modalities to each other were considered. Most importantly, to ensure that differences in perceived realism measured between the conditions can only be attributed to the differences in haptic feedback, only papers were selected where the haptic feedback modality was the only changing variable between conditions. All other variables, e.g., the visuals and tasks needed to be the same between conditions. We identified 38 papers in our selection of papers that fit these criteria. In total these papers have 154 conditions with varying haptic feedback modalities. The following 38 papers were included in the analysis[2]: [1, 3, 7, 10, 16, 17, 19, 20, 22, 25–27, 31, 37, 39, 40, 46, 47, 53, 55, 57, 58, 64, 67, 70–76, 78, 79, 81, 82, 85–87]

5.2 Process of Applying the Framework

Each of the haptic feedback systems from the 154 conditions were assessed with the framework presented in this paper. A score for each of the 14 factors of the *Haptic Fidelity* dimension was assessed. Based on these, a final *Haptic Fidelity* score was calculated as described in subsubsection 4.2.3. For the *Versatility* dimension, one score was selected according to the five categories of versatility. Applying the framework was done by three of the authors in a discussion round to generate consistent and sound ratings. We chose this form of assessment, as the researchers first had to find a mutual understanding for the haptic feedback systems described in the papers and agree on a consistent basis of assessment for each paper. In an initial test evaluation, we found that quite some discussion already happened during reading the paper and the researchers first had to find a mutual understanding of the system as not all aspects of a system were sufficiently described in some papers. As this discussion already included aspects on how to rate the system, we chose a continuous discussion round for the application of the framework. In order to rate each of the presented factors for all conditions, all researchers introduced arguments for a particular rating for the factor. They discussed the arguments until a consensus was found and one final rating was selected that all would agree on. Papers not always reported all information necessary to rate a factor with absolute certainty. Mostly this was the case for the *Software Precision* and *Software Latency* factors as nothing specific was reported about the software (in most cases only the used game engine was reported). The ratings were then based on the assumption that standard practices were used, e.g., collider to calculate the contact with virtual objects.

We provide all ratings of all factors for the 154 conditions including short arguments on why the researchers chose this rating in the supplementary material.

[2]The complete dataset of scores for each of the 154 conditions of the selected research papers is provided in the supplementary materials.

5.3 Statistics

To calculate a correlation between user's perceived realism and the *Haptic Fidelity* of a haptic feedback system we first needed to calculate the effect size of perceived realism between conditions in the 38 selected papers. For the effect size we chose the common metric of the correlation coefficient (Pearson's r), as it is a versatile effect size metric and widely used, e.g., by Cummings and Bailenson [13]. The correlation coefficient was mainly derived from the reported means and standard deviations of the measured perceived realism in each condition from the papers. In cases where this data was not reported, the correlation coefficient was derived from the reported t, F and χ^2 statistics with only one degree of freedom [56]. An effect size was calculated between all conditions of each paper, indicating the effect that the compared haptic feedback methods had on the perceived realism. To calculate the correlation with the *Haptic Fidelity* we used the difference in *Haptic Fidelity* scores for the two haptic feedback methods from the compared conditions and the respective effect size between these conditions. We calculated the final correlation coefficient (Pearson's r) between perceived realism and the *Haptic Fidelity* based on all calculated effect sizes and corresponding differences in *Haptic Fidelity* scores.

5.4 Results

The calculated correlation coefficient between perceived realism and the *Haptic Fidelity* is $r(155) = 0.69, p < .00001$ with a 95 % confidence interval from 0.6 to 0.76 (see Figure 6) and an aggregated sample size of $K = 703$. This indicates that the *Haptic Fidelity* score of the framework is strongly positively correlated to user's self-reported perceived realism of the haptic feedback method according to Cohen [11, 12].

A substantial number of papers (17 of 38) use a standard VR controller with vibration as one of the feedback conditions. One could argue that it is obvious that the effect sizes as well as the differences in *Haptic Fidelity* scores differ greatly between standard controllers with vibrations and elaborate haptic feedback systems and therefore attribute greatly to the strong correlation. To evaluate if the strong correlation is influenced by this comparison, we did a second analysis excluding all conditions that used a standard VR controller with vibration for haptic feedback. For this analysis, we excluded papers that only had two conditions where one was a standard controller (9) and for all other papers we only compared conditions that used other feedback methods than standard controllers. In this analysis 29 papers with 128 conditions were included. The correlation was calculated the same way as described before. For this second analysis we found a correlation coefficient between perceived realism and the *Haptic Fidelity* of $r(110) = 0.8, p < .00001$ with a 95 % confidence interval from 0.72 to 0.86 and an aggregated sample size of $K = 536$. This shows an even stronger correlation

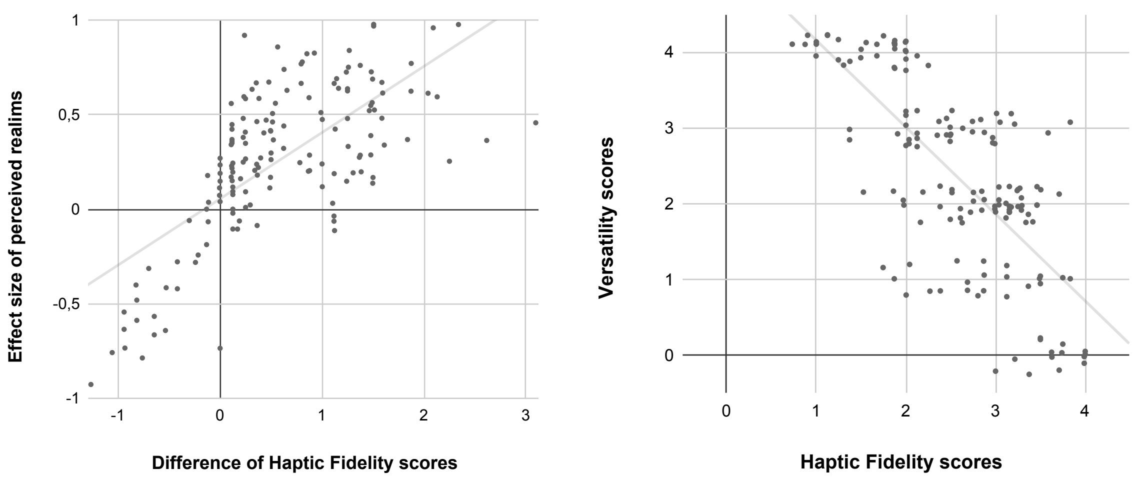

Figure 6: Left: scatter plot with effect size of perceived realism between 154 conditions from the 38 assessed papers and the corresponding difference between the *Haptic Fidelity* scores of the same conditions. Right: scatter plot of the *Haptic Fidelity* and *Versatility* scores from the 38 assessed papers (154 conditions) with a random jitter of .25 for better visualization of the discrete categories for the *Versatility*.

between the *Haptic Fidelity* score and user's self-reported perceived realism of the haptic feedback method than before.

Finally, to investigate the relationship between the *Haptic Fidelity* and *Versatility* dimension of the framework we also calculated the correlation between the *Haptic Fidelity* and the corresponding *Versatility* scores for all feedback systems. We found a correlation coefficient of $r(152) = -0.72, p < .00001$ with a 95 % confidence interval from -0.79 to -0.64 (see Figure 6), indicating a strong negative correlation between the *Haptic Fidelity* and *Versatility* of haptic feedback systems.

We provide all data of the analysis, including the extracted data of all papers, calculated effect sizes, *Haptic Fidelity* and *Versatility* scores and final correlation coefficients in the supplementary material.

6 DISCUSSION

The results of the analysis indicate that the *Haptic Fidelity* dimension of the framework is an indicator for the perceived realism of the haptic feedback in VR confirming our first hypothesis. This makes the *Haptic Fidelity* dimension a valid measure of immersion describing the potential of a system to enable an elevated user experience. Based on the additional analysis, in which we omitted the conditions with vibration feedback of standard VR controllers, we can conclude that the *Haptic Fidelity Framework* is suited for all kinds of haptic feedback systems, especially as there were remarkably diverse feedback systems included in the analysis. The strong negative correlation between *Haptic Fidelity* and *Versatility* scores shows that there is a trade-off between the two dimensions confirming our second hypothesis. A similar trade-off between the realism and versatility of interactions was also identified by Jacob et al. [29] suggesting that this is a common trade-off encountered in interactive systems.

When looking at current systems (see Figure 5), there are no systems falling into the category of abstract but specific feedback. First, this is because abstract feedback is naturally not specific as it can be repurposed to represent a variety of other more specific haptic impressions and second, there is no practical value for designers to build such systems. On the opposite side of the spectrum there are also no systems yet that fall into the category of very realistic but also very generic feedback. Such systems which create realistic feedback for any use case present the ultimate goal of haptic feedback for VR and could someday lead to systems like the Holodeck from Star Trek[3]. The design space offered by our framework should help researchers and designers to understand and compare current feedback systems but also give direction for the development of future haptic devices.

Haptic feedback occurs as a reaction to the interaction with a system and therefore the two are intricately connected. In our framework we try to separate the two as strictly as possible by only looking at output related metrics to solely capture factors influencing the haptic feedback. The interaction can be analyzed in a similar fashion with the framework for interaction fidelity analysis (FIFA) by McMahan et al. [51]. The interplay between haptic feedback and interaction stands out when integrating results from both frameworks (see Figure 2). The FIFA framework for example examines the "kinetic symmetry" describing the involvement of the same forces as in the real-world action. These forces could be created by a haptic feedback system and are described by the *Stimuli* and *Magnitude* factors of our framework. To design and build VR systems that are perceived as extremely realistic both, the interaction and haptic feedback, and their interplay must be considered. Beyond the relation to the user experience and interaction, there are many more factors that are important measures for haptic

[3]https://intl.startrek.com/database_article/holodeck

feedback systems, e.g., cost, portability, setup time, accessibility that can be considered.

With *Haptic Fidelity* our framework provides a measure of immersion assessing perceptual and technical aspects of haptic feedback for VR. While the validation has shown that it is a predictor for one aspect of user experience (perceived realism), it does not cover how users actually experience the feedback. The actual user experience of haptics is based on many factors, e.g., state of mind and past experiences, which can be quite individual for each user [42]. In addition, the haptic perception does not have the same spatial and temporal precision as other senses like vision, making it even more prone to individual interpretation. These aspects of user's individual haptic experience are not captured by this framework. Instead, it is meant to provide researchers and designers with the knowledge which factors can potentially have an influence on the user experience. When rating the individual factors of the framework it is also important to separate the experience part from the actual objective criteria, which should be evaluated. For our validation, we argue that rating the systems by experts, who did not design nor try the systems themselves[4], provides an assessment that is focused on the actual perceptual and technological qualities and not on the subjective experience of using the system. This, of course, requires a comprehensive description about the intent of a system (i.e., the application scenario), the haptic feedback provided and the underlying hardware and software. In our analysis, this information was taken from prototype descriptions in publications and accompanying videos. Within our analysis, the experts had to intensively engage with the information about the systems and in some cases, the experts' judgments could vary. We acknowledge that assessments made with this framework are of a qualitative nature and that the scores provide the means for structuring the results. While the underlying perceptual and technological measures are objective, their assessments naturally are subjective and can be subject to discussion. The ratings for the validation were made by experienced researchers who agreed on a consistent basis of assessment in their discussions forming a solid foundation for our validation process. We also affirm that classifying haptic feedback for a specific application on the single scales requires a certain level of experience with haptic systems, the range of conceivable feedback that could be provided, as well as how the scales integrate this. To address this, we provide detailed explanations with example classification and justifications for each scale of the framework as well as a full documentation of the 154 example conditions that were rated in the supplementary materials for reference. Nevertheless, even with potential small differences in the resulting haptic fidelity score by different evaluators, the framework is valuable for unfolding the influence of the diverse parameters that contribute to haptic fidelity and provides means for comparing different approaches in a structured way.

With this paper we contribute to the general understanding of haptic feedback. While we specifically target VR systems and focus on measures of immersion that are closely related to the field of VR, the definition of *Haptic Fidelity* and the individual factors we identified could as well be applied in general to all kinds of haptic feedback systems. However, one characteristic of haptics in headset-based VR is that haptic and visual feedback can be provided independently, in contrast to haptic feedback in real environments, where the visual appearance of haptic devices or passive haptic props is usually directly perceived by the user. In line with VR-based systems, our framework focuses on aspects of realism of isolated haptic sensing, independently of the visual appearance of the used artifact.

Even though one focus of this paper is to find a single comprehensive measure for *Haptic Fidelity* to compare systems and validate the framework, we emphasize the importance of the individual factors that are presented in this paper. They provide the means to form a deep and structured understanding of underlying concepts of haptic feedback and inform decisions when researching and designing haptic feedback systems. Thus, the *Haptic Fidelity Framework* offers potential to support researchers, designers and practitioners in a variety of situations such as making informed design decisions for haptic feedback and exploring the haptic "design space", estimating potential differences in perceived realism when comparing haptic devices (which in parts could be already possible on a concept level before the devices are actually built), finding detailed explanations for these differences, improving existing haptic devices or addressing the trade-off between realistic and generic feedback.

We acknowledge the following limitations for this work: The types of systems that were analyzed for the validation were not equally distributed, e.g., there were more conditions with custom-built controllers and little to no papers with full-body feedback systems like exoskeletons. This might be due to the existence of less papers on these type of systems and the selection criteria we applied. In addition, when the researchers read the papers to rate the *Haptic Fidelity* of systems for our validation, they could have read or at least looked at the results section of the papers. Even though we encouraged them to not look at results, we did not black them out and it would have been possible to read them. Looking at the results or even graphs about the perceived realism could have influenced the ratings and introduced a bias in the analysis. Furthermore, there might be a general publication bias towards papers with significant differences between haptic feedback conditions, which could have led to an increased number of papers with large effects for our validation.

7 CONCLUSION

In this paper we present the *Haptic Fidelity Framework* providing the means for a structured, comprehensive, and in-depth understanding of factors that influence the realism of haptic feedback in virtual reality. It allows to assess all types of haptic feedback systems for VR. The framework describes the level of sensory fidelity and the resulting capability to produce realistic or abstract feedback in the *Haptic Fidelity* dimension, containing 14 fine-grained factors. A second *Versatility* dimension represents how specific the haptic feedback of a system is for the particular application or if it is more generic and can potentially cover a wider range of applications. We validate our framework by applying it to 154 haptic feedback conditions of 38 research papers on virtual reality applications and compare the *Haptic Fidelity* score to the reported perceived realism.

[4]From the 38 prototypes that were assessed in the analysis, some of the experts had personally experienced four systems before.

The results show a strong correlation suggesting that the framework (1) is well suited to assess haptic feedback systems in VR and (2) describes the potential of a system to create realistic feedback for users. Additionally, we found a strong negative correlation between *Haptic Fidelity* and *Versatility* indicating that most current feedback systems make the trade-off between highly realistic but application-specific and more abstract but widely applicable feedback. While this framework is based on the assessment of perceptual and technological immersion effects, the subjective user experience is also of immense importance when analyzing haptic feedback systems. As current measures, e.g., presence questionnaires, cover haptic feedback only to a minimal degree, in future work we aim to develop a dedicated questionnaire assessing the user experience of haptic feedback systems.

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