# Seeing Isn't Feeling: A Tooling Agenda for Iterative Perceptual Matching in Fabricated Mechanisms


Maties Claesen
UHasselt - Flanders Make
Digital Future Lab
Diepenbeek, Belgium
maties.claesen@uhasselt.be

Stig Konings
UHasselt - Flanders Make
Digital Future Lab
Diepenbeek, Belgium
stig.konings@uhasselt.be

Danny Leen
UHasselt - Flanders Make
Digital Future Lab
Diepenbeek, Belgium
danny.leen@uhasselt.be

Davy Vanacken
UHasselt - Flanders Make
Digital Future Lab
Diepenbeek, Belgium
davy.vanacken@uhasselt.be

Raf Ramakers
UHasselt - Flanders Make
Digital Future Lab
Diepenbeek, Belgium
raf.ramakers@uhasselt.be



**Figure 1: A future workflow for designing the haptic feel of a moving part. (a) The tool in which the designer chooses the motion type (e.g., sliding or rotating) and describes how it should feel, such as clicks or resistance. (b) The system fabricates several swappable internal pieces that can be placed into the 3D-printed object, each creating a different feel. (c) The designer installs the pieces one by one and tries the object to decide which feels best.**


## Abstract

Digital fabrication makes it easy to prototype how artifacts look, yet it remains hard to prototype how moving parts feel when used. For many 3D-printed interfaces such as lids, sliders, dials, and latches, perceived usability and quality depend on the motion's haptic profile. This profile includes resistance, detents, damping, friction, and end-stops. While prior work offers many mechanisms and authoring approaches, designers still face a practical bottleneck. They must converge on a specific intended feel in the final object under real grip, leverage, enclosure contact, and fabrication variation. We argue that tooling should center iterative perceptual matching (IPM), where designers compare candidates in context and refine based on perceived differences rather than low-level parameters. To support this workflow, we outline two physical preview methods. Modular passive props enable fast in-object swapping of fabricated candidates. Reconfigurable haptic peripherals allow rapid programmatic exploration of candidate profiles before committing to fabrication. Building on these directions, we propose an agenda for IPM centered tools that help interpret relative feedback, choose meaningful step sizes, scale control granularity, and maintain perceptual consistency across fabrication iterations.




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## CCS Concepts

**• Software and its engineering → Designing software**; **• Human-centered computing → Graphical user interfaces**; Sound-based input / output; **Haptic devices**; **Contextual design**; **Interface design prototyping**; **• Applied computing → Computer-aided design**.

## Keywords

Haptics, Digital fabrication, 3D printing, Interactive objects, Haptic Experience Design (HaXD), Prototyping, Human-computer interaction (HCI), Mechanism design

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## 1 Introduction

Digital fabrication has made it easy to prototype how artifacts look but far harder to prototype how they feel when users actuate moving parts. In many interactive artifacts, usability and perceived quality hinge on moving parts: the resistance of a slider, the crispness and placement of detents in a dial, the bounciness of a latch, or the damping of a lid. These sensations are not decorative, they shape control discoverability, confidence, and satisfaction during everyday interaction [19, 23, 25]. Yet in typical CAD-to-print workflows, designers can readily specify geometry and motion constraints, while the haptic profile of the motion remains difficult to author, preview, and iteratively refine.

A useful way to frame this challenge comes from haptic perception research. People learn about an object's interactive properties through exploratory procedures, systematic movements that reveal specific tactile/kinesthetic information [11]. One such procedure is part motion testing, where users stabilize an object while applying force to a component to assess how it moves (e.g., buttons, lids, sliders, dials, hinges) [11]. For these interfaces, the motion's haptic profile, including, stiffness, damping, detents, end-stops, hysteresis, is the primary output of the mechanism.

Prior work has substantially advanced the mechanisms and representations available for passive and fabricated haptics. Research has introduced printable and laser-cut structures that embed force feedback and tunable mechanical behavior (e.g., compliant and metamaterial mechanisms, planar passive force feedback) [9, 16, 18, 31]. Other systems explore authoring paradigms for haptic effects, such as parameterized control or sketch-like input [2, 14], and toolkits for tangible proxies and physical computing support rapid fabrication and in-context design [4–6, 13]. Collectively, this body of work expands what can be built; however, it often leaves a practical bottleneck unresolved: how designers converge on a specific desired feel for a moving part.

In practice, designers frequently rely on iterative perceptual matching (IPM) [17]: they try a candidate mechanism, feel it in context, compare it to an intent or reference, and adjust, repeating until the interaction "feels right". This workflow is attractive precisely because haptic goals are hard to specify directly, for designers without extensive tacit mechanical knowledge [24]. A designer may have a clear target experience (e.g., "secure but smooth," "crisp but not harsh," "a gentle notch halfway") without being able to express it as spring constants, contact geometry, or tolerance constraints [24]. Even when a mechanism class is chosen, small geometric edits can yield unintuitive perceptual changes [30], and the final sensation is influenced by the enclosing artifact, the user's grasp and leverage, and even undesired variabilities in fabrication procedures [21]. These factors mean that a desired mechanism in isolation can feel wrong once embedded.

This paper argues that part-motion haptics needs IPM-centered tooling: methods that help designers explore and refine haptic profiles through fast, embodied comparison, rather than requiring them to reason primarily in low-level parameters. Our position is that the key missing capability is not another one-off mechanism, but workflow support that shortens the loop from edits to haptic experience and that makes intermediate prototypes comparable, explainable, and transferable across design stages.

As a position paper, we make three contributions. First, we frame the design of fabricated moving parts through the lens of part motion testing and haptic profiles, highlighting why "seeing" a mechanism is insufficient to predict "feeling" it. Second, we present a literature overview of recurring difficulties hapticians encounter during design and fabrication. Third, we propose a research agenda for tools and fabrication workflows that explicitly support iterative perceptual matching (IPM) throughout the design of digitally fabricated artifacts.

## 2 Walkthrough of Future Workflow

Haptic interactions are everywhere in everyday products, for example in laptop hinges, camera battery doors, kitchen container lids, car dashboard knobs, retractable pens, or tool triggers. Although the proposed workflow could apply to many such cases, we focus the following walkthrough on the following example.

Imagine a designer 3D prints a carrying case for a new game controller as seen in Figure 1. The case includes two common physical interfaces: a lid and a small sliding door that exposes the charging port. Using a typical CAD/CAM workflow, the designer must first decide which parts move and how they move relative to each other (e.g., rotary motion for the lid and linear motion for the sliding door). While prior work provides reusable mechanism [4, 13, 16, 21, 31] concepts for such motions, integrating them into a specific object remains effortful: the mechanism must fit the available space and align with the object's geometry, appearance, and functional constraints.

We use this scenario to illustrate a future workflow based on IPM. The designer begins by defining motion directly in the 3D model, for example by partitioning the geometry at an intended joint location. The system infers the resulting sub-parts and supports selecting a motion type (linear or rotary) and visually setting motion limits (travel distance or opening angle). Next, the designer specifies haptic intent at a perceptual level. For the lid, they may request a distinct click at the fully open state and a satisfying snap on closure to confirm state transitions during use. For the sliding door, they may prefer low, smooth resistance that remains controllable with a single finger. Given these intent cues and the object's geometry, the system proposes a small set of compatible candidates. These candidates are realized as testable alternatives so the designer can judge differences through the part motion exploratory procedure [11].

The number and type of candidates can adapt to the design stage. Early on, the system may generate clearly different candidates to help designers explore the space, especially when they are still exploring possibilities [24]. These candidates sample the structurally plausible solutions without becoming exhaustive. During refinement, it can instead produce smaller variations around a promising candidate along salient perceptual dimensions [30]. This allows the same workflow to support both exploration and fine-tuning.

The designer then evaluates the candidates through interaction (thumb sliding vs whole-hand lid manipulation) and provides relative feedback grounded in what they experienced (e.g., "keep this end-stop, but make mid-travel smoother"). The system uses this feedback to generate the next set of candidates, enabling the designer to converge on a haptic profile through successive, perception-driven refinements rather than direct tuning of low-level mechanism parameters.

# 3 Related Work

## 3.1 Authoring and Communicating Haptic Profiles

Many different approaches to defining haptic profiles have been explored [2, 14, 16, 31, 32]. Shape-Haptics [31] aims to simplify authoring by mapping aspects of "feel" into a geometric design space using vector drawings and a corresponding force-displacement curve. However, previewing and perceptually matching the resulting feel may still require additional iteration. FlexHaptics [16] offers parameter sliders and a set of mechanical module designs (e.g., resistance, detents, bounce) as a way to specify haptic profiles, though the perceptual impact of parameter changes may not be obvious until a new physical version is fabricated. Shape-Kit [32] addresses a related challenge by enabling one person to demonstrate a haptic interaction and communicate it to others. Weirding Haptics [2] supports in-context authoring of haptic effects for VR experiences through higher-level controls, but these abstractions may also limit expressiveness. ChatHAP [14] proposes a chatbot-mediated, natural-language approach to haptic design. However, if the system does not make explicit how it interprets and translates these human descriptions, it risks becoming a black box and undermining designer agency.

## 3.2 Passive Haptic Feedback

Other research [8, 16, 18, 31] pushes digital fabrication toward fabricated feel by embedding passive force profiles into physical interfaces. HapticPrint [27] broadens this scope to passive 3D-printed objects by treating both external and internal haptic characteristics as first-class fabrication outcomes. Shape-Haptics [31] demonstrates how planar, laser-cut compliant spring structures can engage with a shaped sliding profile so that changing the profile geometry changes the perceived force curve. FlexHaptics [16] extends this idea with a modular vocabulary and parametric controls to tune behavior and explore alternative geometries that yield similar profiles. Stay Tuned [21] introduces a 3D-printable bistable mechanism whose actuation force can be quickly and repeatedly tuned after fabrication. Overall, these systems often emphasize improving the design-to-fabrication pipeline, while more incremental, iteration-centered support during in-context design appears less central.

## 3.3 Active Haptic Feedback

HapLinkage, TanGi, and VoxelHap present ways to create moving parts inside their haptic proxies [4, 5, 13]. HapLinkage [13] uses reusable linkage templates with integrated actuation to recreate common tool-like behaviors, such as resistance, stops, and releases. TanGi [4] and VoxelHap [5] instead offer composable building blocks, together with dedicated manipulator elements, to represent multi-part interactions and provide tactile and kinesthetic cues. At the same time, these proxy-based approaches may be less directly suited to in-context mechanism design for fully 3D-printed enclosures. Their building blocks set a lower bound on the feature sizes that can be expressed, they typically rely on active components, and they do not primarily focus on how designers would iteratively author haptic profiles.

## 3.4 In-context Design for Fabrication

In-context design systems bring fabrication workflows closer to real-world use by allowing designers to work with full-scale geometry and physical components [7, 12, 22, 28]. However, while they support in-context geometry, integration, and behavior prototyping, they largely sidestep the authoring and previewing of haptic qualities. The felt characteristics of moving parts remain under-modeled, and the transition from digital to physical behavior is often treated as straightforward.

# 4 Open Research Challenges

## 4.1 Previewing and Iteration Methods for Iterative Perceptual Matching

Iterative perceptual matching (IPM) [17] is an iterative loop: designers try a candidate, compare how it behaves inside the object, and adjust based on the perceived haptic difference. To support this loop, systems should make physical variation easy to preview and swap. We built two illustrative mockups (Fig 2) of envisioned methods that demonstrate contrasting approaches to physical previewing. These mockups are not yet functional, evaluated systems, but prototypes to support discussion.

We consider **modular passive props** as a physical preview method for IPM in Figure 1. The system first fabricates the artifact and its moving parts. The system also fabricates an initial testbed of props as candidates that span both mechanism types (e.g., springs, detents) and key parameters (e.g., stiffness, detent position). A design iteration consists of a single evaluation with one prop candidate: In each iteration, the designer selects a prop from the testbed, installs it in the artifact, and evaluates the resulting haptic feel. Because the props are designed to be hand-swappable (Figure 2a–b), a single testbed can support multiple comparison

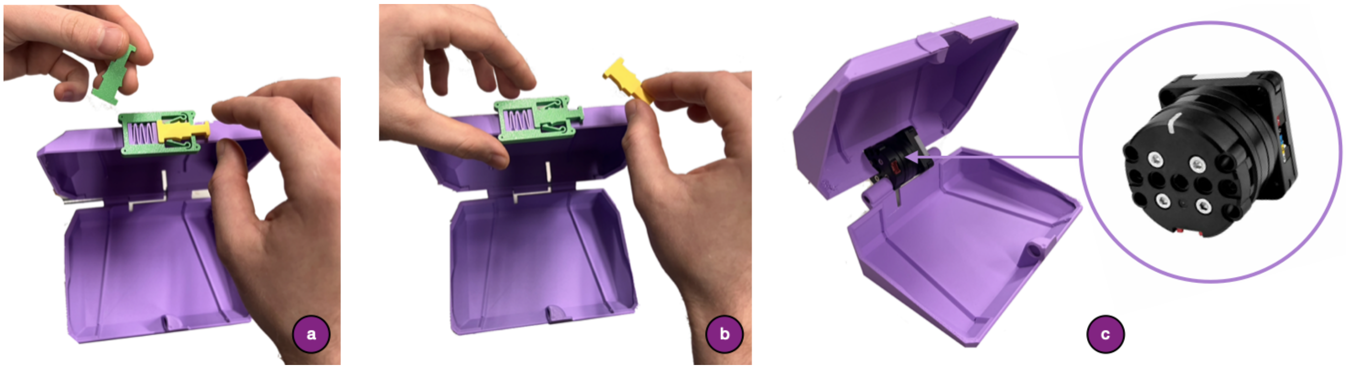


**Figure 2: Two considered physical preview methods for iterative perceptual matching. (a,b) The designer swaps an internal piece inside the 3D-printed object to test a different feel using *modular passive props* (c) a *configurable haptic peripheral* that can be programmed and reused to quickly explore different feels before fabrication by inserting it into the 3D-printed object.**

cycles without reprinting the full artifact. When the current candidates are exhausted or no longer relevant, the designer provides relative feedback to request a different region of the design space (e.g., refined parameters or a shifted haptic profile). The system then proposes and fabricates an updated testbed of prop candidates for the next iteration.

We also consider **configurable haptic peripherals**[1] as a second physical preview method for IPM in Figure 2c. The key difference is how variation is explored. First, the configurable haptic peripheral is installed into the artifact. Instead of fabricating many physical prop candidates, the system proposes a set of digital haptic profiles. These can be emulated by the peripheral. The designer hence can evaluate both the motion and the programmed haptic profile. This lets the same peripheral be used to compare a wider range of behaviors, such as detents at different positions or smooth resistance across the motion.

Both modular passive props and configurable haptic peripherals have strengths and weaknesses. The former can scale to different sizes, form factors, and use cases, from tiny fingertip sliders to large-foot levers. It keeps iteration grounded in the same materials and wear characteristics that will shape the final feel while aiding the designer in understanding the underlying mechanisms. In contrast, a configurable haptic peripheral enables faster, programmatic iteration where UI edits can map more directly to perceived changes and profiles can be adjusted on-the-fly. But it introduces hard limits in embedding-capabilities, weight-support and force/torque range. Exploring multiple interactions in parallel may require multiple devices.

## 4.2 Artifact Specific Characteristics that Influence Haptic Perception

Haptic profiles in fabricated physical interfaces rarely arise from a single mechanism. What users perceive emerges from aspects such as the mechanism and the artifact it is embedded in, and the way it is held and actuated [15]. In handheld artifacts, perception is shaped by stabilizing the object (weight and inertia), varying finger placement (grasp and leverage), and integrating the mechanism into an enclosure (unintended contact, rubbing, or binding), each of which can dampen, mask, or shift intended detents and resistance along the motion path.

Moreover, haptic sensations influence one another. For example [3], a rough or high-friction surface can make an object feel lighter than a smooth one of identical mass [15]. This occurs because higher friction requires greater grip force, which we typically associate with heavier objects. Hence, in-context testing is necessary for designers to recognize and account for these interactions.

Other cues outside of the haptic realm such as sound [2, 30], human interaction variability, and material degradation [31] further reshape what the mechanism feels like in use [3]. To use sound as an example, it can dramatically influence tactile judgements [10, 29]. The acoustic feedback of a hinge or latch can amplify, mask, or even redefine what is felt mechanically. Supporting IPM therefore requires acknowledging that auditory cues actively shape how haptic interactions are perceived. So a research challenge is to develop design and prototyping methods that make these artifact-specific influences predictable and controllable so designers can tune part motion testing in-context and achieve feels that remain consistent across realistic grips, tolerances, and usage conditions.

## 4.3 Interpreting Relative Feedback in Iterative Perceptual Matching

With the recent surge of AI systems, particularly large language models [14] capable of interpreting nuanced natural language, there is an opportunity to better support how designers articulate and refine haptic intent. An IPM-centered tool could introduce a clear middle step between what a designer wants something to feel like and how it is physically built: the designer describes a goal in everyday terms, called descriptors, using for example adjectives or metaphors [25], the system suggests which perceptual qualities [1, 26, 30] are involved and which low-level parameters, geometries, or surface properties could be adjusted to achieve them [16].

Because IPM relies on side-by-side comparison, feedback is often articulated relative to an in-world reference (e.g., "make it slightly more resistive than candidate A", "make it a combination of candidate A and B"). The challenge is that relative suggestions encode

[1] https://docs.m5stack.com/en/unit/Unit-RollerCAN

both a direction and an implicit magnitude, yet the magnitude is rarely specified explicitly. This is compounded by the weak perceptual grounding of common numeric descriptors (e.g., Newtons, friction coefficient, torque), which do not map transparently to haptic perception. The system could make its interpretation explicit by revealing which underlying parameters it adjusted using the previously mentioned mapping (e.g., increased baseline drag by X%, sharpened detent slope, reduced post-detent hysteresis). This would allow designers to accept, reject, or refine these transformations.

## 4.4 Granularity of Control for Authoring Part-Motion Haptic Profiles

Relative adjustments can support coarse tuning, but they may break down when designers aim for more intricate haptic profile designs. An open challenge is to characterize the level of user control and parameter detail that is necessary and sufficient to author haptic profiles [20]. It should be investigated when high-level comparative input provides enough leverage, when more explicit specification becomes required [2, 24], and how much added detail can be introduced before designers are effectively pushed back into low-level parameter reasoning. This balance is likely to vary by expertise. Novices, who lack tacit mechanical intuition, may benefit from more structured comparisons and guided scaffolding, whereas experienced hapticians may only occasionally rely on such support and instead seek fine-grained in-context control to reach precise perceptual targets. Too little control can prevent reaching specific haptic patterns, while too much control can undermine the accessibility benefits that motivate comparative, in-context tuning.

## 4.5 Maintaining Perceptual Consistency Across Fabrication

In prototyping practice, designers often progress from one-off rapid prints to fabrication approaches that improve robustness, reliability, or repeatability in small runs. This progression raises an open research challenge for haptic profiles in physical interfaces: how can a profile remain perceptually consistent as a design moves across representations and fabrication methods? Even when a designer targets “the same” profile, the felt outcome can drift at each handoff. For example, detent crispness is perceived relative to the surrounding baseline feel (e.g., steady drag). If that baseline changes across representations, an identical detent amplitude can be experienced as more or less salient [16, 23, 31].

A concrete example of this is the case of active haptics, as seen in Section 4.1. The use of this introduces a follow-on step: once a digital profile is selected, translating that programmed feel into a digitally fabricated mechanism is not trivial, because the final digitally fabricated artifact must be designed to reproduce the same force and motion behavior.

# 5 Discussion

Haptic interaction does not emerge from geometry alone, but from the interplay of material, mechanism, and multisensory cues. While much of this work has focused on 3D printing, a broader discussion must consider how alternative materials and fabrication techniques fundamentally shape perceived interaction. Expanding the material palette opens new expressive dimensions that go beyond geometry and force profiles, and invites a wider view of what counts as a haptic design variable.

This perspective can be extended by explicitly treating texture, sound, and other multimodal cues as first-class variables within iterative perceptual matching. Designers could intentionally shape and refine texture and sound alongside mechanical attributes. Doing so would expand IPM beyond purely force-based adjustment and support a richer, more holistic approach to multimodal interaction design.

Building on this multimodal perspective, future tools could learn mappings that preserve a consistent perceived feel even when contextual factors change, such as differences in size, material, or actuation style. Instead of treating each new configuration as an entirely separate design problem, the system could help designers maintain perceptual equivalence across variations. At the same time, it could establish a shared and explicit language for collaboration across designers, engineers, and fabrication contexts, supporting the kind of cross-disciplinary communication [23].

Taken together, the open research challenges we outline form a coherent agenda for continued exploration. Addressing them will require new tools and empirical studies to understand which forms of input, feedback, and preview most effectively support in-context refinement.

# 6 Conclusion

Designing how 3D-printed mechanisms feel for part motion testing remains difficult because haptic profiles are hard to specify and iteratively refine in context. We argue for IPM as a guiding workflow and outline tool directions that support rapid comparison while making fabrication-driven changes in feel easier to anticipate.


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