Blended Physical-Digital Kinesthetic Feedback for Mixed Reality-Based Conceptual Design-In-Context

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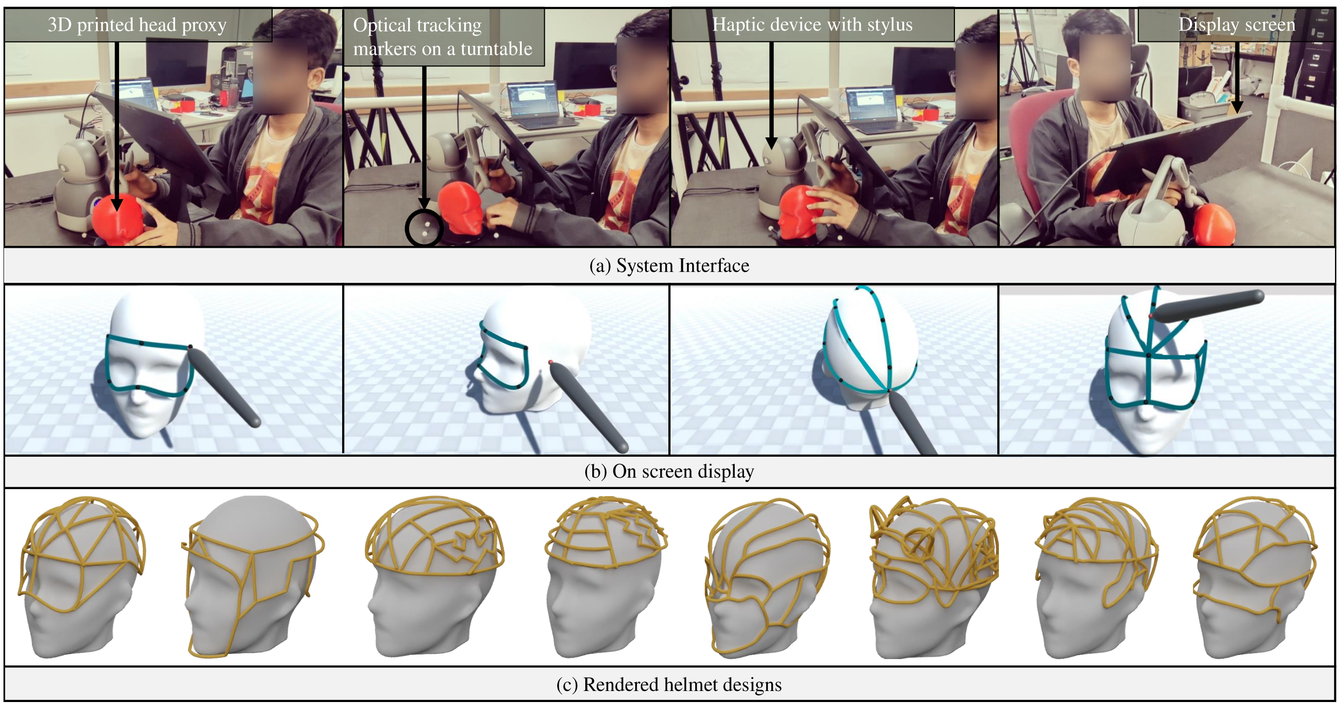

(a) System Interface

(b) On screen display

(c) Rendered helmet designs

Figure 1: A user generates different wire-frame models of a helmet using an optically tracked 3D printed head proxy model and a haptic device. The user explores different design ideas by defining a curve network on top of a mesh model. The physical manipulation of the head proxy along with the curve network are visualized on a flat screen in real-time. The bottom row displays an example of a completed wire-frame helmet design with integrated protective eye-gear.

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ABSTRACT

In this paper, we investigate blended physical-digital kinesthetic feedback (or *blended haptics* in short) as a means for controlled three-dimensional design ideation in mixed reality (MR) environments.

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We define blended haptics as a spatial interaction wherein a physical object (e.g. a 3D printed human head) provides a specific design context for a user to generate ideas through physical manipulation of and on the object (e.g. drawing a digital sketch of a helmet) in the virtual environment. Using 3D wire-frame modeling as a concrete digital prototyping context, we investigate this idea of blended haptics in terms of how it supports design cognition specifically in spatial user interfaces. For this, we implemented a modeling tool as an experimental setup that allows a user to directly create curve-networks (wire-frame models) on a physical object (i.e. a contextual proxy) with one hand while simultaneously controlling the object with the other hand using a tracked turn-table. The key idea is that the user can simultaneously experience kinesthetic feedback from both the physical objects as well as the digital wire-frame models. To systematically investigate our approach, we conducted a comparative user evaluation of conceptual design tasks performed by two groups of users, one with the blended haptics (e.g. physical head and digital helmet) and the other with purely digital haptic feedback (e.g. digital head and digital helmet). Our study shows that blended haptics required less physical effort in the design task and resulted in concepts with higher novelty score as compared to using purely digital haptic feedback.

CCS CONCEPTS

• **Human-centered computing → Interaction design**.

KEYWORDS

Haptics, Curve modeling, Tangible Interaction

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1 INTRODUCTION

1.1 Context & Motivation

Three-dimensional idea generation in virtual, augmented, and mixed reality (VR/AR/MR) has been extensively studied in the past decade with the advent of new spatial interaction technologies [24, 25, 29, 81, 87]. There are many works that study prototyping-based design ideation in MR environments [1, 28, 44, 49, 62, 88]. Prototyping in early-stage design ideation has been noted to be advantageous over sketching in terms of mitigating fixation and leading to better integration of functionality [7, 94]. The key requirement, however, is a fine balance between the speed and fidelity of prototyping to support creative cognition [55, 84]. Here, MR can play a clear role in bridging the gap between the designer's perception, action, and cognition through embodied interactions.

To date, the *mixing* of digital and physical spaces in *mixed* reality occurs primarily in terms of visual feedback. While one can view digital objects superimposed on the imagery of the physical environment, the kinesthetic and proprioceptive sensory modalities are not well-integrated during spatial manipulation of digital objects. This integration is crucial to enable the type of precise actions that are both natural and necessary for performing spatial tasks involving design cognition [52, 58]. The challenge is to integrate the tangibility of close range interactions of the physical world within current MR interfaces. In fact, this observation is echoed by Kent et al. in the spectra of replicability, flexibility, tangibility, and validity, where virtual prototyping clearly requires much research attention [30]. In this paper, we envision a new type of a MR-based digital prototyping workflow, where the central idea is to create a seamless *kinesthetic and proprioceptive integration of digital and physical environments.*

1.2 Basis & Rationale

Fine motor skills are inherently present in tasks that involve creating, building, and repairing physical artifacts. Such precision in human actions is made possible through a confluence of close-range visual, kinesthetic, and proprioceptive bi-manual control. As an example, let us consider an illustrative example of soap carving as an example of a task that requires precise bi-manual visuomotor control. A soap carving task can be seen as a high-precision action taking place in the *hand—object—object—hand* kinematic chain which is being closely and simultaneously monitored by the eyes. In this chain, the two objects, soap and tool, are essentially a part of the sculptor creating the carving in keeping with Gibson's view of ecological psychology [17]. We argue that this close-knit visuo-kinesthetic system is essential for creative spatial design tasks wherein the designer must necessarily forget about the artificial constructs imposed by digital artifacts and immerse completely in the act of idea exploration[12, 32, 67]. Our work focuses on studying the symbiotic relationship between the designer's action, the designed artifact, and the design tool by integrating real life and simulated haptic feedback in MR interactions.

Our technical goal is to develop and evaluate interactive mechanisms that enable a user to seamlessly use physical objects within virtual environments in order to conceptualize and explore a variety of ideas during early design phases. This is akin to how we typically make things in real life; we design things in context by re-purposing the objects in our vicinity and invent our own use of those things. Toward this goal, we introduce the concept of *blended physical-digital kinesthetic feedback (or blended haptics in short)* as a spatial interaction wherein a physical object (say, a 3D printed human head) is used as a means to provide a specific design context for a user to generate ideas through physical manipulation of and on the object (say, drawing a digital sketch of a helmet) in the virtual environment.

1.3 Approach & Contribution

To systematically investigate the concept of blended haptics, we take inspiration from wire-frame modeling as a means to create early design concepts. For this, we implemented an MR-based modeling system for creating 3D curve networks directly by using a haptic stylus to create digital curves on top of a real-life physical object that is controlled using a tracked turn-table (Fig. 1). The novelty of this setup is that it integrates real-world kinesthetic feedback that results from the contact between the stylus and the physical object with a virtual haptic feedback to emulate wire-bending while creating the curve networks. Additionally, we implement virtual kinesthetic feedback mechanisms to provide guidance during design editing tasks. Furthemore, our camera-based turn-table enables the user to simultaneously re-orient the physical object to enable continuous and seamless curve modeling and editing using bi-manual interaction. This allows users to leverage their tacit knowledge of precise, bi-manual physical manipulation that inherently integrates visual, proprioceptive, and tangible sensory modes.

Our central hypothesis is that such an interaction would allow the user to focus on the creative task of design by minimizing the cognitive load involved in using current AR/VR/MR interfaces for quick-and-dirty design conceptualization. To test this hypothesis, we conducted a between-subjects comparative user study with 38 participants divided equally in two groups. By utilizing helmet and shoe as our design contexts, we evaluate the two user groups where one group generated ideas using blended haptics (3D printed models of a head and shoe last) and the other group is subjected to purely digital haptic feedback on virtual proxies of the stimuli (3D meshes of the head and shoe last).

Finally, we present a detailed quantitative and qualitative analysis comprised of (1) inter-rater reliability studies of concept quality using established design ideation metrics, (2) a quantitative study of manual energy consumed during ideation in each group, and (3) self-reported measures of cognitive load and creativity support from study participants. A comprehensive cross-examination of these metrics showed that the use of blended haptics enabled participants to create a wider variety of concepts while using lesser physical effort.

2 LITERATURE REVIEW

2.1 Physical Prototyping for Design Ideation

Prototyping is a valuable tool in promoting creative idea generation in early design and has been shown to correlates with better design outcomes [92]. Lim et al. noted that prototypes can be tools to explore the design space in that they are "*purposefully formed manifestations of design ideas*" [39]. Gerber notes that low-fidelity prototyping affords design practitioners the opportunity to learn from failures thereby providing them confidence in their creative ability [15]. Viswanathan et al. noted that physical prototypes supplement novice designer's mental models [82, 83]. Prototypes have also been viewed as tools for reflection in the early design stages [11, 21]. A study by Häggman et al. noted that prototyped designs were generated more quickly as compared to those created by CAD [19]. In fact, the efficacy of low-fidelity prototyping goes as far back as the work by Rudd et al. [70] who noted that the key advantage of low-fidelity prototyping is in supporting the refinements in product requirements and preliminary analysis in the early stages of design. In the context of engineering design, works by Menold et al. provided a framework for structuring prototyping methods based on feasibility, viability, and desirability for better design outcomes [47, 48]. Lauff et al. provides a strategic tool to help designers plan meaningful prototypes to explore certain design questions [37].

Despite the increased interest in computational fabrication research to support, enable, and enhance physical prototyping, there are only a handful of tools that bridge the gap between design and prototyping [87]. Much of the prior work in creativity support, typically undertaken in the computer graphics and HCI communities focuses on purely digital prototyping [74]. To that effect, even much of virtual, augmented, and mixed reality systems for design primarily focus on the creation of the digital artifact [16, 86].

2.2 Digital Prototyping for Design Ideation

There is much recent work on digital prototyping in the design, graphics, and HCI literature [2, 3, 7, 89]. In this work, our specific focus lies in the domain of curve-network prototyping, i.e. the physical production of wire-frame structures as abstract representations of the design concepts. For instance, Peng et al. demonstrated a novel workflow wherein a user could model and edit a wire-frame model that was being simultaneously 3D printed along side the modeling interface. Another intriguing work is *TrussFab*, a system demonstrated Kovacs et al. [33] that builds large-scale structures on desktop printers. Works by Muller's group on low-fidelity fabrication [53, 54] are particularly intriguing in this regard. Specifically, they showcase three different prototyping workflows to demonstrate different levels of abstraction (brick-based, wire-based, and laser-cut plate-based) in prototyping systems.

2.3 Spatial User Interfaces for Design Ideation

Our work is inspired a special class of "*situated*" modeling as well as prototyping frameworks that showcase the utilization of existing objects in the user's surrounding for getting inspiration for new ideas [8, 26, 36]. Further, we also draw upon works that have specifically demonstrated wire-frame and curve design tasks in mixed reality environments, such as *WireDraw* [95], *NapkinSketch* [5, 91]. Finally, we take inspiration from works that highlighted the use of proxies for virtual design tasks. In these, *ProxyPrint* is an excellent example that studies how physical proxies could be leverages for craft activities [80].

2.4 Augmented Reality in Haptics

The integration of Augmented Reality (AR) with haptic feedback has changed user interaction within mixed reality environments. It has enhanced the immersive experience by combining visual and tactile stimuli [4]. Researchers have developed wearable haptic devices for hands and fingers that provide vibro-tactile feedback to improve dexterity by emulating friction and pressure [63, 79, 90, 93, 97]. In conceptual design, the integration of haptic feedback has allowed designers to manipulate virtual objects as if they were real, enabling rapid prototyping and design ideation [10, 31, 65, 88]. Physical proxies, such as 3D-printed models and tools paired with haptic feedback, significantly improve design evaluation and refinement [18, 68, 71]. AR haptic systems have also been used in remote manipulation, training, and skill acquisition. In fields requiring precision like surgery, AR haptic systems provide realistic environments and elevates user experience [18, 22, 61]. The integration of AR and haptics significantly enhances mixed reality environments, improving user interaction and performance across various applications. As technology advances, AR haptic systems will likely play an increasingly important role in design, training, and remote manipulation.

2.5 Proprioceptive Feedback in Bi-manual Spatial Interactions

Mechsner et al. [46] highlight the presence of both perceptual and spatial symmetry for bi-manual motions. Contrary to the traditional viewpoint, which infers a connection between homologous muscles, in this case, the upper limbs, co-activation. Furthermore, Hatem et al. [23] evaluate stroke-related rehabilitation training focusing on non-invasive brain stimulation, robot-assisted training, and immersion in virtual reality. Additionally, they offer a decision tree that proposes a customized rehabilitation strategy based on the substantial literature and features of stroke patients. The analysis also highlights the need for more research into bi-manual coordination because preliminary studies indicated improved recovery. Latimer et al. [35] also underlined the value of bilateral exercise in post-stroke recovery techniques. The fact that the ipsilateral corticospinal pathways, which are essential in recovering from hemiplegia, are also found to be active in bilateral movements was used by Burgar et al. [43] to support the notion of bilateral training. Few articles [41, 45, 60] explore bimanual rehabilitation as a type of physical coupling wherein people help each other restore the function of the injured limb using the unaffected limb. This is because both arms move in unison and symmetrically due to receiving identical neurological signals from the brain. One benefit of bimanual rehabilitation is that it allows us to attain results akin to constraint-induced treatment without externally restraining the injured upper limb.

2.6 Wire-frame Modeling for Digital Prototyping

The capacity to swiftly externalize ideas is a critical component of the work because of its emphasis on early-stage design ideation. While formalized computer-aided design tools have become more accessible, and increasingly collaborative, their utility in conceptual design is still questionable [56]. Ideation typically requires a high-speed low-fidelity modus operandi that promotes the controlled vagueness germane to the conceptualization process [13]. Therefore, a quicker, flexible, and simpler workflow is crucial to reduce the cognitive load on the designer and facilitate creative thinking [9, 38, 64, 66, 69].

Wire-frame modelling has been used previously to produce ornamental shapes [96]. We find that most conventional modeling tools utilize a highly detail-oriented parametric workflow that can prevent capturing of fleeting ideas and stifle creativity during early-stage design [76]. Therefore, we seek a low-fidelity 3D modeling process that lets users quickly communicate ideas in 3D form with the least amount of work and without requiring specifics. Recent developments in sketch-based 3D modeling methods take advantage of our innate capacity to draw with a pen to produce 3D creations [57].

Such techniques allow users to construct 3D shapes by simply sketching their 2D outlines, while the backend system infers the intended 3D geometry [27], [72]. With ease of use and efficiency, wireframe sketch-based 3D modeling tools are highly amenable to creative design ideation processes. Here, we presented a 3D modeling tool—driven by a similar sketch-based approach—which supports design creation and transfer of design data between the physical and the virtual world. Further, this tool allows for seamless integration of our software features within the modeling workspace and helps maintain consistency of interactions during modeling and collaborative operations.

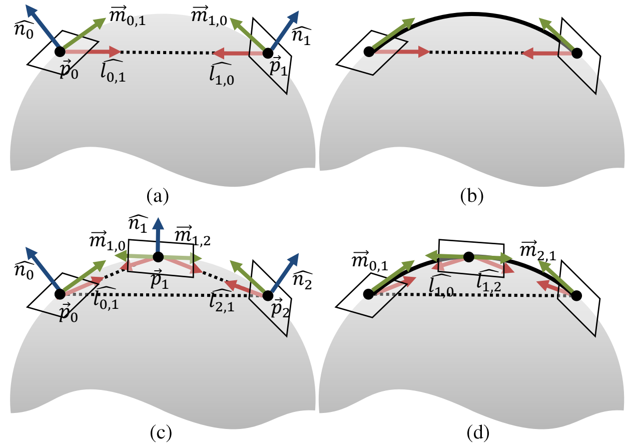


Figure 2: An illustration of curve initialization. The system generates the curve by defining the tangents based on underlying mesh geometry.

Building on our prior preliminary experiments [65], we choose wire-frames as a modeling metaphor in our study. The idea is to maintain a low-fidelity three-dimensional representation of the prototype while avoiding biases associated with well-defined, rather prescribed, geometric models.

3 COMPUTATIONAL FRAMEWORK FOR BLENDED HAPTICS

Our computational framework consists of two main components corresponding to the geometric modeling and kinesthetic feedback, which are integrated together to facilitate a hybrid ideation workflow. Further, the geometry of the physical object and the curve network together govern the kinesthetic feedback provided by our framework. Here, we discuss the design representation, ideation workflow, introduce a new force-guided digital wire-bending technique.

3.1 Design Representation

We use 3D curve networks as a prototypical representation of design concepts as wire-frame model created *around* a physical object acting as a contextual proxy. A curve network $\mathcal{N}(V, E)$, in our case, is defined as a graph with vertices V and edges E. Here, each vertex $(\vec{p}, \{\vec{m_{a,b}}\}) \in V$ is a pair defined by a position vector $\vec{p} \in \mathbb{R}^3$ and a set of tangent vectors $\{\vec{m_{a,b}}\}$. For each edge $(i, j) \in E$, we define the geometry of the edge as a cubic Hermite spline between $(\vec{p_i}, \vec{m_{i,j}})$ and $(\vec{p_j}, \vec{m_{j,i}})$ in V, as given by:

$$\begin{aligned}\vec{p_t} &= (2t^3 - 3t^2 + 1)\vec{p_i} + (t^3 - 2t^2 + t)\vec{m_{i,j}} \\ &+ (-2t^3 + 3t^2)\vec{p_j} + (t^3 - t^2)\vec{m_{j,i}}\end{aligned} \tag{1}$$

Here, $\vec{p_t}$ is an interpolated point in the curve for parameter $t \in [0, 1]$. We chose cubic Hermite splines because it ensures that

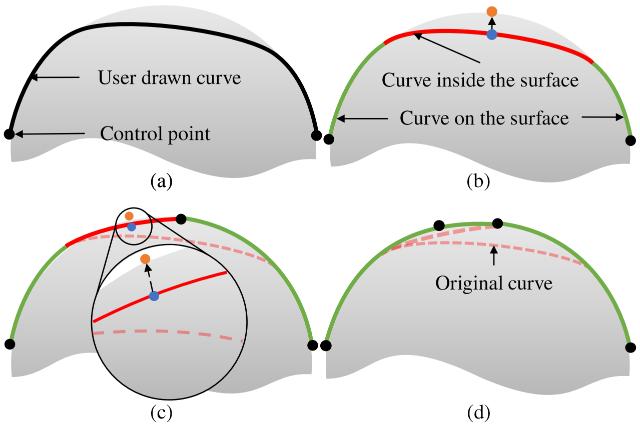


Figure 3: An illustration of multi-component refinement of the curve by the system once a curve is defined by the user. The system identifies the portion of the curve that is inside the model mesh and then refines the curve until the entire curve is outside the mesh.

the interpolated curve passes through the control points $\vec{p_i}$ and $\vec{p_j}$ while maintaining C^1 continuity between any two curves in the network sharing the same end-points. Apart from the curve network itself (i.e. the design concept), we also maintain a virtual mesh model ($\mathcal{M}$) that mirrors the physical object being used as the contextual proxy in the design process.

3.2 Ideation Workflow

We envision our design ideation workflow in terms of three main modes that a user may potentially enact in an iterative manner as defined below:

- **Manipulation:** The manipulation mode is defined as the instance where the user physically rotates the physical object using the turn-table tracked using a camera setup (see details in section 4.1). This allows the user to both visually inspect the physical object so as to take creative decisions on how to develop the design and also to actually access a desired region of the stimulus geometry to create the curves..
- **Probing:** Probing mode is defined as the instance when the user is in the process creating the prototype based on the decisions taken in the inspecting phase. This mode is a combination of the direct physical interaction that the user has with the model as well as our kinesthetic force feedback depending on the curve network that the user is drawing. We use the metaphor of probing since the user is "drawing" the curve network by sampling multiple points along the surface of the model using the haptic stylus as a probe.
- **Editing:** Editing mode is defined as the instance when the user is editing the existing curve network by manually changing the position of control points using the haptic stylus.

The design of a curve network, therefore, typically begins with the user probing a sequence of points on the physical object. This results in a chain of cubic Hermite curves. The user may keep on adding more chains resulting in a network of curves. Once a reasonable curve network is generated, the user may wish to make edits by displacing the control points (i.e. the vertices of the curve-network). Note that, manipulation can happen in tandem with probing or editing. Therefore, at any given instant, all vertices of the current curve network are transformed based on the rotation of the turn-table. In the ensuing sections, we provide methods to enable these interactive modes from a geometric as well as a kinesthetic perspective.

3.3 Geometric Modeling

There are three main issues that need to be addressed in the geometric modeling of curve networks, namely: (1) initialization of a single curve on the surface of the physical object, (2) refinement of a curve to ensure the curve to be constrained one the surface, and (3) creation of the curve network topology from individually generated curves.

3.3.1 Curve Initialization. Given two points $\vec{p_0}$ and $\vec{p_1}$ that are probed on the surface of the physical object, our first aim is to determine the corresponding tangent vectors, $\vec{m_0}$ and $\vec{m_1}$, in order to generate a cubic Hermite spline. We achieve this by using the mesh model in conjunction with the points probed by the user (Fig.2(a,b)). We begin by determining the faces f_0 and f_1 on $\mathcal{M}$ that are closest to $\vec{p_0}$ and $\vec{p_1}$ respectively. Note that we use the centroids of the faces to estimate distances. Consequently, the tangents $\vec{m_{0,1}}$ and $\vec{m_{1,0}}$ are simply given by the cross-products $\hat{n_0} \times (\hat{l_{0,1}} \times \hat{n_0})$ and $\hat{n_1} \times (\hat{l_{1,0}} \times \hat{n_1})$ respectively. Here, $\hat{l_{0,1}}$ is the unit vector from $\vec{p_0}$ to $\vec{p_1}$ and $\hat{l_{1,0}}$ is the unit vector from $\vec{p_1}$ to $\vec{p_0}$. Further, $\hat{n_0}$ and $\hat{n_1}$ are faces normals for f_0 and f_1 respectively. Note that $\vec{m_{0,1}}$ and $\vec{m_{1,0}}$ computed are co-planar leading to a planar curve.

During curve creation, we assume that users would typically probe more than just two points in a sequence (Fig.2(c,d)). Consider an initial spline between two points $\vec{p_0}$ and $\vec{p_1}$. When the user adds a point $\vec{p_2}$, we simply create a second spline between $\vec{p_1}$ and $\vec{p_2}$ wherein a new tangent $\vec{m_{1,2}}$ is appended to the tangent list at $\vec{p_1}$. Here, $\vec{m_{1,2}}$ is essentially the cross-product $(\hat{n_1} \times \hat{l_{1,2}} \times \hat{n_1})$ where $\hat{l_{1,2}}$ is the unit vector from $\vec{p_1}$ to $\vec{p_2}$. Generalizing this, we can say that for a sequence of probes $\{\vec{p_0}, \ldots, \vec{p_{k-1}}\}$, the curve network $\mathcal{N}(V, E)$ would simply be defined by $V = \{(\vec{p_0}, \{\vec{m_{0,1}}\})\} \cup \{(\vec{p_i}, \{\vec{m_{i,i-1}}, \vec{m_{i,i+1}}\})\} \cup \{(\vec{p_{k-1}}, \{\vec{m_{k-1,k-2}}\})\}$, where $i \in [1, k-2]$.

3.3.2 Curve Refinement. It is obviously not true that a spline defined using our method will always remain on or above the mesh $\mathcal{M}$. This may especially be more likely when the end points of the cubic Hermite are defined on high curvature regions or are farther apart on the mesh (Fig.3). To resolve this problem, we refine the spline by applying an iterative curve splitting approach. Consider a spline between $\vec{p_0}$ and $\vec{p_1}$. We first compute the set of interpolated points on the spline that are inside $\mathcal{M}$ and consider the point $\vec{p}$ in this set that is farthest from the surface $\mathcal{M}$. We then find the projection $\vec{q}$ of $\vec{p}$ on the surface $\mathcal{M}$. Finally, we split the original spline into two splines based on the sequence $\{\vec{p_0}, \vec{q}, \vec{p_{k-1}}\}$ based on the algorithm in the previous section. In other words, we get a spline defined between $\vec{p_0}$ and $\vec{q}$ and a second spline between $\vec{q}$ and $\vec{p_1}$, and between $\vec{p_m}$ and $\vec{p_1}$. We repeat this method after each split until none of the splines are inside the mesh.

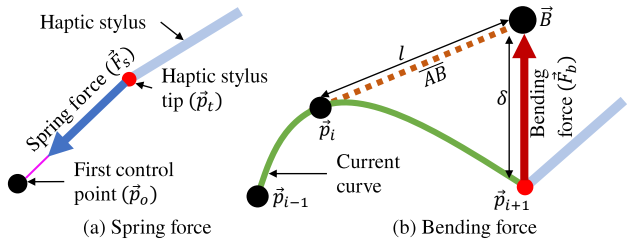


Figure 4: An illustration of the (a) spring force and (b) bending force experienced by the user.

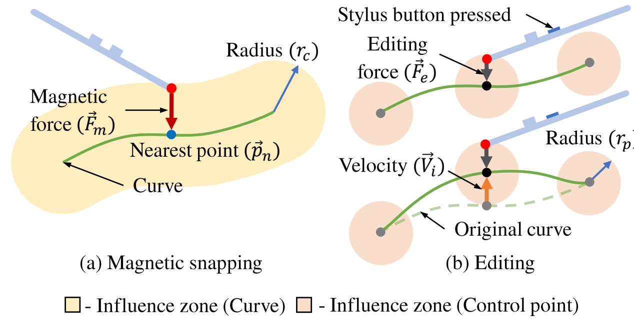


Figure 5: An illustration of the (a) magnetic snapping force and (b) editing force experienced by the user.

3.3.3 Curve Network Topology Generation. The third and final step in our geometric modeling method is the creation of a curve network topology. Note that this includes the ability to create closed loops as well. For this, we employ a simple method based on control point snapping based on point-to-curve proximity. Given a network $\mathcal{N}(V, E)$ and a new point $\vec{p}$, we first determine the closest point $\vec{q}$ on the curves in $\mathcal{N}(V, E)$. Suppose $\vec{q}$ lies on a curve defined by and edge $(i, j) \in E$. Then, we split the spline between $(\vec{p_i}, \vec{m_{i,j}})$ and $(\vec{p_j}, \vec{m_{j,i}})$ into two splines defined from $\vec{p_i}$ to $\vec{q}$ and $\vec{q}$ to $\vec{p_j}$. Note that new tangents are added at $\vec{p_i}$ and $\vec{p_j}$ along with an updated edge list. Once again, the process of splitting is identical to that mentioned in previous sections. In cases where a user wishes to create a closed loop (which is is typically signified by the user probing the last point close to the initial point in a sequence), we simply use a distance threshold to determine proximity and simply add a spline based on a cyclic edge order. In any case, the final representation of our curve network remains consistent.

3.3.4 Kinesthetic Feedback. In order to enhance the controlability of the curve during mid-air interactions, we provide kinesthetic feedback constrained by the curve geometry. Work by Mohanty et al. [50], showed the role of kinesthetic feedback for drawing 3D curves on planar surfaces and their 3D rotations. Providing kinesthetic force to guide curve creation in virtual environments enhance the user performance as explored in some of the earlier works by Wacker et al. [85] who studied the effects of providing surface and line guidance to users to virtually sketch/trace on physical objects and compared that to sketching on virtual objects. Machuca et al. [42] also provided smart 3D guides to help users improve their 3D virtual sketches. In another work by Panda et al. [59] developed morphable surfaces to provide tangible feedback to users while sketching on top of virtual objects in VR.

We provide different types of kinesthetic force feedback during the entire process of wire-frame modeling. We divide it into two parts based on whether the user is creating new curves or editing an existing curve. We provide three different types of force feedback during the process of curve creation. These different feedback mechanisms are described as follows:

- **Spring Force:** As soon as the first control point is defined, the haptic device starts providing a spring force feedback ($\vec{F_s} = -K_s(\vec{p_t} - \vec{p_0})$), which is directly proportional to the distance between the current haptic stylus tip position ($\vec{p_t}$) and the previous control point ($\vec{p_0}$) (Fig. 4(a)). Based on initial pilot studies, the spring constant K_s was set to be 0.35 in our implementation.
- **Bending Force:** Along with the spring force feedback ($\vec{F_s}$), a bending force feedback ($\vec{F_b}$) is also provided. The bending force is calculated based on the metaphor of force required to bend a metal wire. This metal wire is modeled as a straight circular cantilever beam whose one end (fixed end) is fixed at the last defined control point ($\vec{p_i}$) and the other end (free end) is attached to the stylus tip ($\vec{p}_{i+1}$) which moved in 3D space (Fig 4(b)). As the stylus tip moved in space, the bending force ($\vec{F_b}$) and spring force ($\vec{F_s}$) changed dynamically. The steps for calculating the bending force are as follows:
  (1) Compute the length of spline (l) between $\vec{p}_{i+1}$ and $\vec{p_i}$. This is considered as the length of the cantilever beam being deformed.
  (2) Draw a line segment $\overline{AB}$ of length l originating at $\vec{p_i}$ along the tangent at $\vec{p_i}$ in the direction of $\vec{p}_{i+1}$.
  (3) Calculate the distance (δ) between the free end $(\vec{B})$ of $\overline{AB}$ and $\vec{p}_{i+1}$. This can be considered as the deflection of the cantilever beam $\vec{AB}$.
  (4) Calculate $\vec{F_b}$ according to the following equation:
  $$\vec{F_b} = K_b \frac{\delta}{l^3} \hat{n} \quad (2)$$
  where $K_b = 0.35$ is a constant based on the initial testing and $\hat{n}$ is the unit vector along the line joining the free end of $\vec{AB}$ and $\vec{p}_{i+1}$.
  $$\hat{n} = \frac{\vec{p}_{i+1} - \vec{B}}{\|\vec{p}_{i+1} - \vec{B}\|} \quad (3)$$
- **Magnetic Snapping:** To help users create control points directly on any existing curve, the system provides a magnetic snapping force ($\vec{F_m}$). The existing curves have a radius of influence ($r_c = 0.1$) around them. The magnetic snapping force gets activated if the haptic stylus tip ($\vec{p}_t$) comes within the radius of influence (r_c) of any existing curve. Also, when $\vec{F_m}$ is activated, both the spring force $\vec{F_s}$ and bending force $\vec{F_b}$ are deactivated. The magnitude of this force is directly proportional to the distance between ($\vec{p}_t$) and the nearest point ($\vec{p}_n$) on any curve. The value of proportionality constant ($K_m = 0.35$) is determined based on initial testing.

$$\vec{F_m} = \begin{cases} -K_m(\vec{p}_n - \vec{p}_t), & \text{if } \|\vec{p}_n - \vec{p}_t\| \leq r_c \\ 0, & \text{otherwise} \end{cases} \quad (4)$$

The system provides two types of kinesthetic force feedback while editing the existing wire-frame model. These force feedbacks are magnetic snapping ($\vec{F_m}$) as described earlier and an editing force ($\vec{F_e}$). The editing force is defined as follows:

- **Editing Force:** Similar to the spring force ($\vec{F_s}$), we provide an editing force ($\vec{F_e}$) while the user is editing the position of an existing control point. Similar to curves, each control point has a radius of influence ($r_p = 0.1$) around them. The magnetic snapping force gets activated if the haptic stylus tip ($\vec{p}_t$) comes within the radius of influence (r_p) of any existing control point. If the stylus tip is within this radius of influence (r_p) and the user presses and hold the back button of the haptic stylus, the editing force is activated (deactivating the magnetic snapping force $\vec{F_m}$) which is directly proportional to the distance between haptic stylus tip ($\vec{p}_t$) and the nearest control point ($\vec{p}_i$) on any curve. The value of proportionality constant ($K_e = 0.35$) is determined based on initial testing.

$$\vec{F_e} = \begin{cases} -K_e(\vec{p}_i - \vec{p}_t), & \text{if } \|\vec{p}_i - \vec{p}_t\| \leq r_p \\ 0, & \text{otherwise} \end{cases} \quad (5)$$

4 INTERFACE DESIGN & SYSTEM IMPLEMENTATION

Our physical setup consists of a haptic device to provide kinesthetic feedback, an optical motion tracking camera system, a monitor screen to visualize the actions, optically tracked custom designed and 3D printed turntable, and a physical object. Details about the study setup can be found in Sec: 4.1. Below we discuss some factors that we considered while designing the interface.

- **Spatial Configuration:** The relative location of action space with respect to the body is a key factor in spatial user interfaces (SUI). We utilize action field theory to determine the motor control afforded by the system based on the proximity of the physical object to the user [6]. We design the interactions such that the actions performed by the user are close to the body. This space is generally referred to as the peripersonal space. Galigani et al. made a note that active tool-usage (haptic stylus in this case) in the user's peripersonal space enhanced their proxemic perception, allowing for precise control of actions [14]. Hence, using a small space close to the user's body gives user a better chance at placing the control points in a precise manner. We draw inspiration from prior work by Mohanty et al. to co-locate visual and action space to perform bi-manual tasks in user's peripersonal space [51]. The haptic device also imposes some physical constraints based on it's range of motion. To overcome the range limitations of haptic device, we place the physical object on top of the 3D printed turntable such that it is close to the user's body while also keeping it accessible via the haptic stylus.
- **Feedback:** The system provides three types of feedback: (a) Visual feedback through rendering of the drawn curve along with a digital rendering of the physical object, (b) tangible feedback from physically touching the object with the stylus tip, and (c) kinesthetic force feedback by the haptic device based on the curve geometry (Sec. 3.3.4) and the digital rendering of the physical object.
- **Modeling:** We choose curved networks to model the prototypes. Curved networks offer a good representation for quick prototyping and similar to sketches in 2D, 3D curve networks still have the ability to express overall shape without the necessity of complex 3D modeling. Also, curved networks use lesser time and material to manufacture by using traditional rapid prototyping techniques. To increase the speed of prototyping, we choose to sample points on the surface of the object rather than drawing continuous curves. Sampling points along the object surface is a low energy task and demands less motor control as compared to drawing continuous 3D curves.

4.1 System Setup and Implementation

We build our experimental setup keeping in mind the aforementioned factors as follows:

- **Hardware Setup:** Our hardware setup (Fig.1(a)) consists of 10 Optitrack Flex 13 motion capture cameras (field of view: 56°; refresh rate: 120 Hz) mounted on a custom gantry built using PVC pipes, measuring 5 ft x 4 ft x 8 ft in volume. Our setup also comprises of a 3D Systems Touch haptic device capable of providing a maximum force of 3.3 N. An Alienware 15R3 laptop computer with an Intel Core i7 − 7700HQ CPU (2.6GHz), 16GB of GDDR5 RAM, and a NVIDIA GeForce GTX2070 graphics card, running 64-bit Windows 10 Professional Operating System was used. Our application is developed in Unity3D game engine using the 3D Systems OpenHaptics®, and OptiTrack Unity plugin along with the OptiTrack Motive API for streaming motion capture data to Unity3D. The application is mirrored on a monitor screen. The participants used three different 3D printed models mounted on a custom designed and 3D printed turntable (Fig.6).
- **Setup Design:** Our experimental setup is designed to facilitate a co-located visual and action space which is visually and perceptually coherent to facilitate precise bi-manual actions in a MR environment. To achieve this, we take inspiration from Mohanty et al. and use a sequential visuo-motor configuration of Eyes followed by Screen followed by Hands[51]. We placed the haptic device and the physical models behind the screen. The user is not able to see the physical models and the haptic stylus directly because it is occluded by the screen. We display a virtual representation of the haptic stylus and the physical models on the screen. These models serve as a supporting surface on which, a user draws curves by sampling control points on the surface. Since the 3D printed models are not tracked in physical space, they are fixed on top of a custom designed 3D printed turntable with reflective markers attached to it. The rotation of the turntable is tracked using the OptiTrack Motive API. The position of the haptic device and the turntable is also fixed on a table, making sure that the relative position of the models doesn't change with respect to the haptic device during the study.

4.2 User Interactions

In order to create curve networks, we utilize the two buttons present on the haptic stylus: forward and back button. The user starts drawing the curve by clicking the forward button. This marks the start of probing mode and adds a control point at the stylus tip position at the time of the click. This also activates the kinesthetic

Figure 6: 3D printed turntable and proxies of physical objects used in the user studies are shown from different angles. These include: (a) Turntable, (b) Cube used for target reaching task, (c) Head model, and (d) Shoe model for wire-frame design task.

feedback for curve creation. Then the user moves the stylus to another location to add another control point. On moving the stylus to the desired position, the user clicks the forward button to add another control point. This way, the user creates the desired number of control points. The user can press the back button to stop drawing the current curve, which also deactivates the kinesthetic feedback for curve creation. On pressing the back button, the kinesthetic feedback for editing gets activated. The user is now simultaneously in inspecting and editing mode. In order to edit the position on an existing control point and subsequently change the curve network geometry, the user brings the stylus tip The user then repeats the process multiple times as desired.

5 EXPERIMENT DESIGN

The experiment was designed to allow participants to create quick prototypes in 3D space and to compare between two interface setups, namely, *virtual* and *physical*. We designed two sets of tasks for each setup to measure the quantitative and qualitative aspects of the workflow. In the quantitative experiment, the participants were asked to locate and pick points on a cube using the haptic stylus so as to establish a baseline of the accuracy they can achieve on the surface. In the qualitative experiment, participants generated curve networks on digital and physical models in order to design various models in a set amount of time. We observed how participants interacted with the digital and physical model while making these curve network designs.

The *physical* group was provided with a 3D printed counterpart of a digital model that was being shown on the screen, while the *virtual* group relied solely on the haptic feedback received from the haptic device to get a feel of the model.

5.1 Participants

We recruited 38 participants (19 per group, with a split of 10 males and 9 females in the *physical* group, and 11 males and 8 females in the *virtual* group) enrolled in undergraduate, and graduate programs at the university. The participants belonged to the age group of 18-49 years with backgrounds in engineering, health sciences, and liberal arts. Most participants didn't have any experience of sketching in virtual interfaces or using a haptic device.

5.2 Procedure

Each user study lasted between 75 to 90 minutes. The participants were briefed about the setup and given a short tutorial on how to use the interface and its various functions. We then explained the task specific actions that they had to perform.

5.2.1 Task 1: Target Reaching. Given a random sequence of target points identified on a primitive shape, the task was to touch the tip of the haptic stylus at the target points followed by a button-press to indicate completion. This is a fundamental task in the assessment and understanding of motor skills [78]. Specifically, the primitive chosen in our study was a cube of dimension 8 cm and the target points (Fig. 6(b)) were 5 face-centers (excluding the one at the bottom face), 12 edge-centers, and 8 corners. For each target, we collected data for three trials resulting in a total of 75 trials per participant. Before beginning the formal trials, participants were allowed to familiarize with the task using 5-10 trials. Subsequently, a random sequence of target points was generated for each participant. Participants were allowed to rotate the turntable as necessary and there was no restriction in terms of the starting point of the stylus.

5.2.2 Task 2: Wire-frame Design. The goal of this task was to measure the difference in user performance and creativity between the *physical* and *virtual* groups, in an open-ended design task. For this, the participants were first familiarized with the user interface and interactions for drawing and editing curve-networks in our design workflow. Participants were then given a practice task where they were asked to create a wire-frame on a simple capsule-shaped object for 5 minutes. They were allowed to ask questions regarding the features of the setup and the test administrator offered guidance during the task. After familiarization and practice, each participant was given the following design tasks: *"Design superhero themed helmets and shoes which will be used while riding a bike - fit for children aged between 5 – 10 years. The final design should be safe, comfortable, should fit the user, and should be aesthetically pleasing."* In order to avoid any learning effects, we also randomized the order of the helmet and shoe alternatively across the participants.

5.2.3 User Feedback. After the tasks, each participant was asked to respond to a questionnaire comprised of the NASA Task Load Index (NASA-TLX [75]) for both the tasks. For the design tasks, we further asked the participants to rate their creative experience using the creativity support index [40]. Following this, we conducted a a semi-structured interview where we elicited participants' experience regarding the basic user interactions, the design tasks, as well as their design choices.

5.3 Data Collection & Metrics

5.3.1 Data Collection. For each user we collected multiple data points including the control points of the user-generated cubic Hermite spline, interpolated points, stylus tip positions, rotation of the turntable, and the haptic stylus button press events. We also collected video data of the user study by making screen recordings

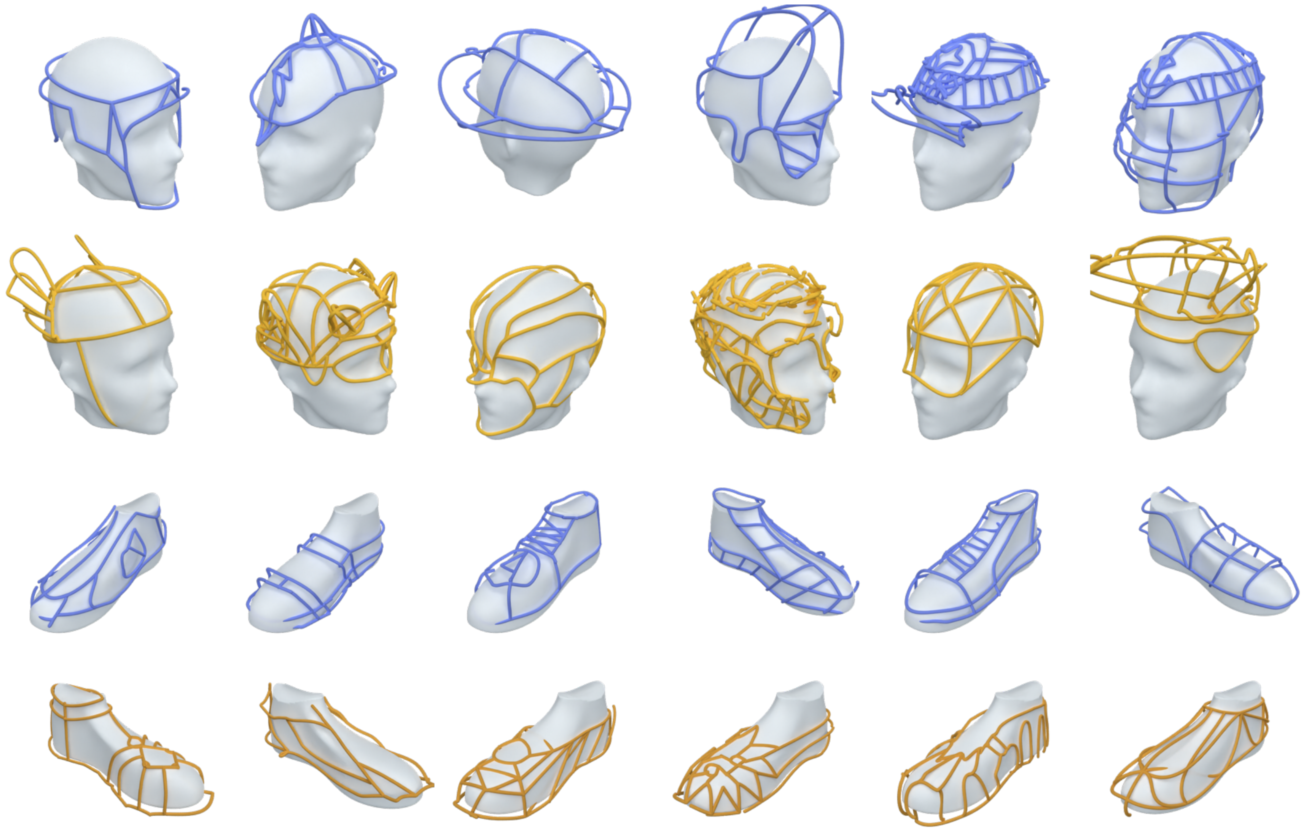


Figure 7: Some curve-networks generated by the users during the Wire-frame Design task of designing helmet and shoe in *physical* (blue) and *virtual* (yellow) setting.

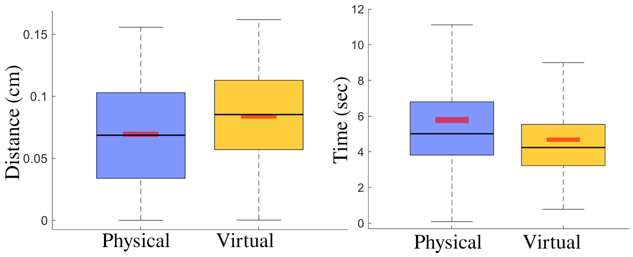
of the interface and video recording of the user performing the tasks.

5.3.2 Metrics.

- **Completion Time & Accuracy:** For the Target Reaching task, we collected data on the amount of time the user took to reach the next target. There was an allowable threshold around each of the targets in which the user could perform the button-press action in order to indicate completion. We also measured how far off the user was from the target at the time of the button press, and if they were inside the threshold limit.
- **Ideation Metrics:** Two expert raters evaluated the curve networks that were generated by the users. The raters selected were unaware of the study design and any information regarding study assumptions and hypotheses other than the final networks created. Further, the curve networks generated by the *physical* and *virtual* groups were randomized in order and de-identified before being assigned to the raters. Both the raters were senior graduate research students in engineering and product design disciplines. The raters were asked to rate each curve network based on well-established Novelty and Variety metrics from Linsey et al.[40]. Each rater first constructed a list of clusters (say: $C_1, \ldots, C_n$) and subsequently calculated the variety score of each curve network as the percentage of clusters present in the respective curve network. The novelty score for the ideas was calculated by considering the number of other ideas present in the same cluster. That is, the lower the number of ideas in a cluster, the higher the novelty. The following formula was used for the evaluation of the novelty, where N_j (eq.6) is the Novelty score of the j^{th} idea, T is the total number of ideas, C_i is the number of similar ideas in the i^{th} cluster, S is the set of all clusters that the j^{th} idea occupy, and n is the number of clusters occupied by the j^{th} curve network.

$$N_j = \frac{1}{n} \sum_{i=1}^{|S|} \left(\frac{T - C_i}{T} \right) \quad (6)$$

We also asked the raters to rank each users' shoe/helmet designs based on the number of factors (0 to 4) that a design might have considered, to give a Quality metric per model.
- **Energy Consumption:** We computed the kinetic energy by accounting for the movement of the stylus (position and rotation) and the turntable rotation throughout the process



(a) Error for each target (b) Time taken for each target

Figure 8: A comparison of the error and time taken for target-reaching task (Task 1), shows that while participants were more accurate using the physical interface, they took similar time on average with respect to the virtual interface.

of each curve network design using the eq.7.

$$K.E. = \frac{1}{2}\phi^T M\phi \tag{7}$$

where ϕ is the twist vector $\in \mathbb{R}^6$ of the object coordinate frame, M is the inertia matrix of the object being manipulated $\in \mathbb{R}^{6X6}$.

6 RESULTS, USER FEEDBACK & DISCUSSION

We recorded a total of 2850 trials (75 trials per user for 38 users) of Task 1, and 228 curve networks (3 designs per model, 2 models per user for 38 users) for Task 2, a few of which are shown in Fig.7. From these user studies, we wanted to explore how blended haptics and tool usage relate to each other in the context of design ideation. We wanted to answer the following questions:

- Which type of haptic feedback reduced the barrier to entry in tool usage? Why?
- Which haptic feedback offers the potential for improved design ideation?
- Does a reduced barrier of entry correlate with improvement in design ideation? If so, why, and how?

6.1 Blended Haptics and Tool Usage

By examining the accuracy and completion time for the first task and the surface deviation in Task 2, we examined whether a tangible signal lowers the difficulty to use the tool (the developed system). We first tested the data for normality using the Kolomogrov-Smirnov test. We found that the data is not from a normal distribution. We further conducted hypothesis testing using Kruskal-Wallis test ($\alpha = 0.05$) which is the non- parametric statistical equivalent of one-way ANOVA test. We subsequently performed post-hoc analysis using the Dunn's test for statistically significant results. Additionally, we examined and contrasted the results of the NASA-TLX survey for both tasks and the typical energy used by users while performing the tasks.

6.1.1 Intent and Time. For a tool to be used effectively, the tool should act as intended by the user while the user spends minimal cognitive energy in trying to understand or learn the of a tool. The tool should feel as an extension of their own body. In the target reaching task, the users were asked to reach specific target points shown in random order. The data collected from this task shows that the users of the *physical* group could reach closer to the target point (their intent), with the median value of the error being 0.068 cm, compared to the 0.085 cm of the *virtual* group users (Fig.8).We also saw that even though the users reached closer to the intended point in the case of the *physical* group, they generally took longer time, with the median being 5.01 seconds, compared to the *virtual* group's 4.24 seconds . Less than 5 percent of the points in both the interfaces were outliers, with the maximum for the physical being 32.47s and the maximum for virtual being 23.92s. We conducted hypothesis testing using Kruskal-Wallis test since the data was not from a normal distribution. We found statistically significant difference between the two groups for the error ($p = 6.88e - 22$) and time taken ($p = 1.218e - 29$) to complete the task.

6.1.2 Perceived Workload. At the end of each task, the users were asked to fill out a questionnaire comprising of the NASA-TLX [20] to quantify and compare the various mental loads that a user experiences during the tasks. We hypothesized that the *physical* group users would report lower mental and physical demand, higher performance satisfaction, lower perceived task difficulty, and lower frustration while using the system. We found that the data was not from a normal distribution using the Kolomogrov-Smirnov test. The results showed that for all the metrics, there was no significant difference between the two interfaces ($p > 0.1$), despite users of the *physical* group being more accurate and taking lesser time.

6.1.3 Energy Spent. With users getting closer to the target points in the *physical* case, we also wanted to see if there was any trend in how users interacted with a particular interface. To study this, we calculated the energy spent by each user in manipulating the turntable with their non-dominant hand and the stylus with their dominant hand. The energy was calculated in terms of the Kinetic energy spent by the user in rotating or translating the objects.

We saw that users of the *physical* group spent more energy compared to the *virtual* group users. We observed statistically significant difference between the two groups for the energy spent by the dominant hand and the overall energy spent during the task ($p = 0.0148$ for dominant hand, $p = 0.2488$ for non-dominant hand, and $p = 0.0203$ for both hands combined). From observational analysis, we could tell that the difference was due to the presence of the physical cube. In both the interfaces, the stylus tip couldn't enter the cube region either because of a physical obstruction from the 3D-printed cube in the *physical* interface or due to the haptic feedback from the digital cube in the *virtual* interface. But naturally, the physical cube also obstructed the other parts of the haptic device, like its arms, when a target point appeared on the other side of the cube. Upon realisation that the cube was being an obstruction (sometimes after multiple failed attempts at reaching the target directly without rotating the cube), the user would rotate the cube to make the target point readily accessible for completion of the trial. All this resulted in higher energy expenditure for both the hands of the users of the *physical* group. This movement scenario also can be the reason why the *physical* group users, on average, seemed to take a slightly longer time to complete each trial.

6.1.4 Tendency to be Close to the Surface. We hypothesized that with a physical object present in front of them for them to touch

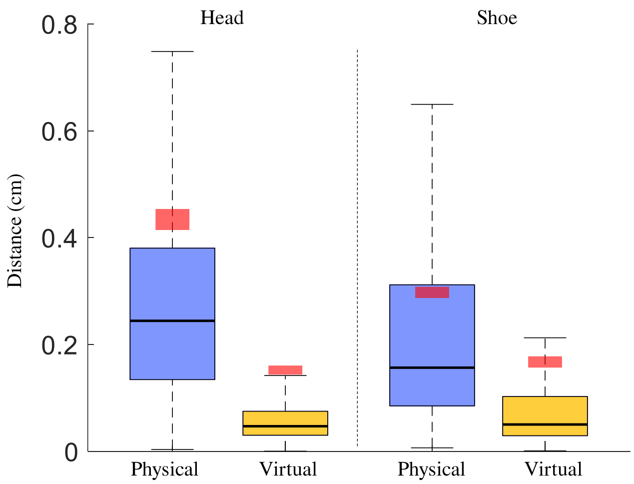


Figure 9: A comparison between the distances at which curves are drawn in each interface shows that users of the physical group have a higher tendency to keep away from the objects, possibly due to the presence of tangible feedback available to them via their non-dominant hand

with the stylus or with their non-dominant hand, a user would draw their curves closer to the object when compared to the *virtual* interface. We observed contrasting results as compared to our hypothesis. The curves drawn with the physical setup from the surface of the digital object, were at a mean distance of 0.235 cm for the head and 0.159 cm for the shoe, while for the virtual setup, these values were 0.058 cm and 0.062 cm, respectively (Fig.9). Using the Kruskal-Wallis test, we found statistically significant differences between the virtual and the physical groups($p \approx 0$). We further conducted the post-hoc analysis using the Dunn's Test and found out that there are significant pair-wise differences between physical and virtual group for both head and shoe models. Around 10 percent of the data points are outliers, with the maximum for physical being 9.4767 cm for the head model and 4.378 cm for the shoe model. Similarly, around 10 percent of the data points are outliers for the virtual setup, the maximum of which is 4.3784 cm for the head model and 5.926 for the shoe model.

From observational analysis, we think users were more likely to draw away from the object because when a user could feel the object with his non-dominant hand, they were more confident about the space around the object, which opened up their design space in a spatial sense. Meanwhile, users of the virtual interface remained close to the surface during the drawing process since that was the only mode of tangibility available to them during the curve-design process.

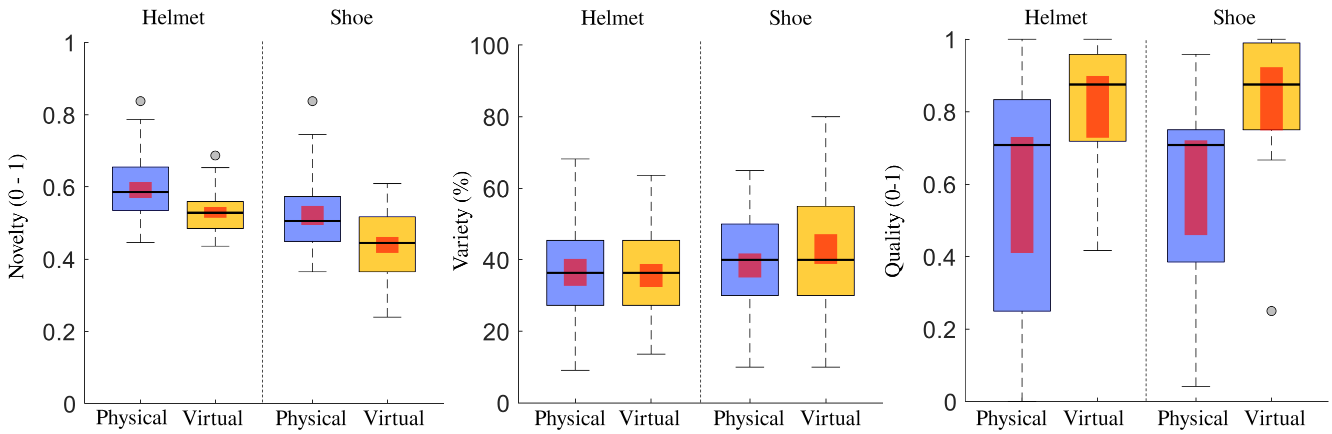
6.2 Blended Haptics and Ideation

Our aim here was to analyze the designs in terms of novelty, variety, and quality (Fig.10). We further seeked to understand the manual energy spent in the two interfaces and how it related to the design outcomes. We tested the data used for the analysis below for normality using the Kolomogrov-Smirnov test. The data was found not to be from a normal distribution.

6.2.1 Rating the Designs. Both the interfaces offered some variation of tangible feedback to their users. We wanted to see if either of these variations resulted in the users performing better in the ideation phase of the design. The generated designs were presented to the raters for them to judge the designs and rate them in their Novelty, Variety, and Quality. For the novelty, variety, and quality metrics, the Fleiss's kappa value was between 0.72 and 0.75 showing a substanital inter-rater agreement [34, 73]. On a scale of 0 to 1, we see that the *physical* group received better Novelty ratings for both the head and shoe models, with the median for the *physical* group being 0.586 and the median for the *virtual* group being 0.526, with the p-value (using Kruskal Wallis test) of this comparison being $2.7027e-09$. A higher novelty rating means that a user created more unique designs than the other users of their own group. From the comparison, we see that the *physical* groups could generate more new ideas, possibly due to the presence of a physical object in their hand that they could touch and which resulted in a better understanding of the model and higher spatial awareness of all the features on the model. Meanwhile, the variety rating shows what percentage of the design space a curve network represents. This rating is similar for both the interfaces (median 36.36%, $p = 0.6067$), indicating the presence of a physical object within the interface has no effect on how much of the design space a user can explore.

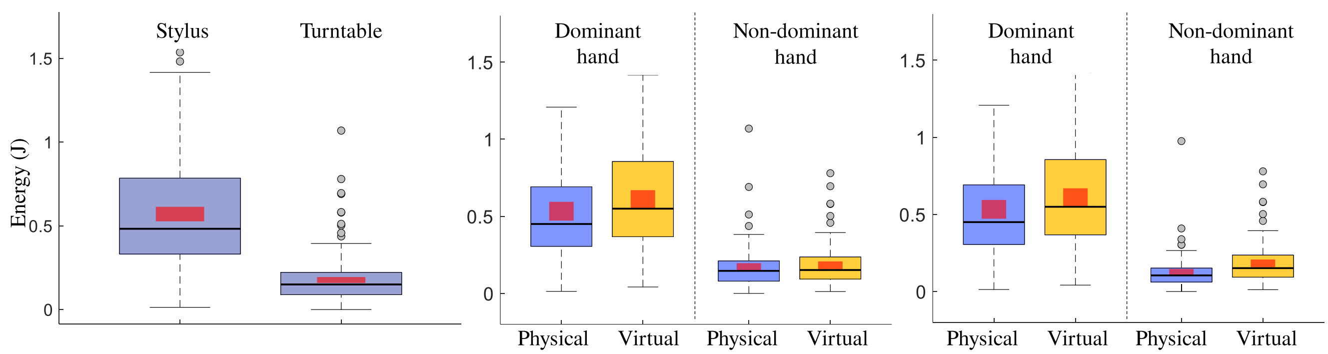
On the other hand, the quality ratings go the other way showing us that the *virtual* interface helped users make designs of a higher quality. The quality rating was calculated by keeping a tally of the number of factors a user incorporated into their design. As a result, we may conclude that the *virtual* work maintained a comparable range of quality for both models, whereas the *physical* group experience spans a much more comprehensive range of characteristics and has substantial variances for the two models.

6.2.2 Energy Spent. Both groups spent notably more energy with their dominant hand than with their non-dominant hand (0.48 J vs. 0.15 J), per design, in the wire-frame design task (Fig.11) We found significant differences between the two groups using Kruskal-Wallis hypothesis testing with $p \approx 0$. We further analyzed the energy spent by each hand separately. Comparing interfaces for each hand, for the dominant hand, we saw that the median is lower for the *physical* group and since the p-value is 0.0128, the result is statistically significant. On the other (non-dominant) hand, the energy spent per design is very similar for both interfaces. This difference, however, was not statistically significant ($p = 0.426$), as expected. In the case of the *physical* interface, the kinetic energy calculations also have an additional mass of the object included in them. This leads to higher energy values. If we ignore the object on the turntable, we see that the *physical* group users put in lesser effort with their non-dominant hand (0.105J vs 0.152 J, $p < 0.001$). Combining the energy values of both hands, we see that the *physical* group users spent significantly less energy creating the designs. Using the Dunn's test, we found that there is a statistically significant difference between the two groups for both head and shoe models. With a higher novelty score, lower object manipulation effort, and generally positive user feedback, the *physical* comes up to be the better choice between the two interfaces, allowing a user to explore new designs with a reduced physical effort.



(a) Novelty (b) Variety (c) Quality

Figure 10: A comparison between the various ideation metrics ratings. The physical interface afforded the users to create more novel designs, while the variety ratings were similar for both the interfaces. We see an increase in the quality ratings for the virtual designs.



(a) Energy spent by each hand across both interfaces (b) Energy spent by each hand (considering model weights) (c) Energy spent by each hand (NOT considering model weights)

Figure 11: (a) A comparison between the energy spent by the dominant hand using the stylus and the non-dominant hand using the turntable, shows that users spent more energy using their dominant hand. A comparison of the energy spent by the dominant and non-dominant hand between both the interfaces, shows no statistically significant difference between the interfaces, (b) when objects weights are considered, and (c) when object weights are not considered.

6.3 Tool Usage and Ideation

While evaluating the results, we observed that the manipulation and control of the virtual objects were easier as compared to their physical counterpart in this particular study. In the case of ideation, although the *physical* interface allowed a user to create more novel ideas, we saw that either interface allowed the users to explore the design space to a higher degree.

6.3.1 User Behaviour. Most users in the *physical* group held the object directly and rotated it instead of manipulating it through the turntable. Upon inquiry after the tasks, users mentioned doing so helped them understand and develop better spatial awareness of the system since they couldn't directly see the physical object or the stylus. These users relied on their visual senses (and keeping the stylus further out from the object) to perform bulk motions of the stylus and rotation of the object or draw base curves of their curve-network design, but then switched to feeling the object through the stylus (either the haptic feedback in case of the *virtual* group or the physical object in case of the *physical* group) and utilize their proprioceptive abilities. The *physical* group differed from the *physical* in the fact that these users were able to feel these objects with both their hands, and it felt more natural to them.

6.3.2 Motor Strategies. With the goals of monitoring and identifying essential motor strategy categories for completing the experimental tasks and generating specific hypotheses for quantitative analyses, we started by thoroughly analyzing videos of user study sessions throughout the studies. We wanted to study how users interacted with the interface concerning the kind of strategies they employed to achieve the task goals. We formulate the following

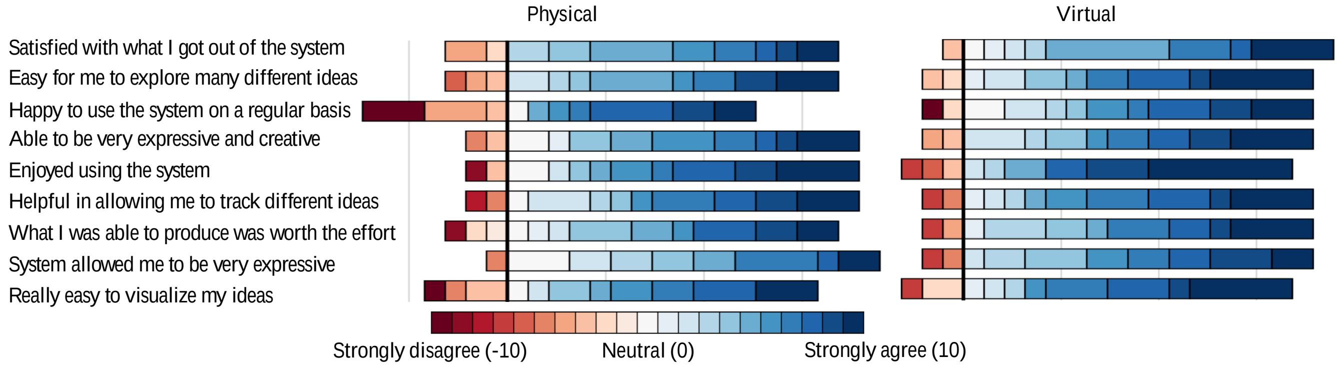


Figure 12: User feedback on the creativity support offered by the system using the Creativity Support Index. Overall feedback for our system was positive.

hypothesis based on our observational performance indicators for a particular shape geometry between the two *physical* and *virtual* groups: *Virtual* group should facilitate similar motor strategies concerning the *physical* as they both afford kinesthetic feedback. Consequently, there should be no statistical importance, and the performance of the *virtual* should be equivalent to the *physical* in terms of completion time and docking accuracy, and the statistics should not show any significant differences. Compared to the *physical*, *virtual* group should do the docking with less precision and more slowly. This ought to have an impact on completion time and accuracy statistics.

6.3.3 User Feedback. The feedback from users was generally positive, with most users agreeing that adding some kind of tangibility to a designing interface helped them visualize the 3D designs effectively, and this can also be seen in the CSI survey (Fig.12) that the users answered. Users liked how the curves could be modified, allowing them to "correct" their designs. Many users of the *virtual* group were also very fascinated by how the tangible feedback worked, allowing them to "feel" the object with their stylus.

A few users struggled a bit with getting used to the haptic feedback from the curve network and could not perform as well as the other users. Users also complained about not having a delete option for the curves and just an undo/redo button available, which forced them to incorporate any unwanted curves that they created earlier in the design. This also led to lower CSI scores by some users. We expected this feedback since our goal was not to develop a full-fledged feature-rich system. However, this is a seemingly small yet extremely important feature to consider for future studies. Furthermore, our current system only offered yaw rotation on the turn-table. This also caused discomfort for some users because of physical restrictions on the movement of their non-dominant hand.

7 LIMITATIONS & FUTURE WORK

The system allowed the physical object to be only manipulated by yaw rotation. This reduced the overall design space a user could explore and forced them to think of specific areas of the model more than the others. Although the system allowed bi-manual interaction to a certain degree, a complete six degree-of freedom control will lead to a true spatial bi-manual interaction in the working volume. This may further allow us to expand on the various metrics such as manual effort as well as ideation effectiveness. As far as the system development is concerned, our current implementation was primarily developed as an experimental setup rather than a feature-rich modeling system. However, some users indicated the need for features such as the ability to undo, delete, copy, and select curves. However, even these seemingly simple functionalities may need careful design of interaction techniques when considering new haptics modalities (e.g. snapping to a curve, etc.). Some interactions (e.g. undo) may even be implemented as standard events using combinations of stylus buttons and menus. Some users also struggled in judging how far their stylus was from the virtual or physical object, hence starting to draw curves from a point far away from the surface. Adding or improving visual cues such as advanced shadow rendering and perhaps proximity based haptic cues may help mitigate this issue. Another important feature that can be added is the ability to create non-planar splines. For this, newer modes for curve editing with novel kinesthetic feedback is important to investigate. An interesting future study with a feature-rich system could be to explore varied degrees of prototyping fidelity with perceived risk as previously suggested by Stakey et al. [77] for concept selection.

8 CONCLUSION

Our primary objective in this work was to investigate blended haptics as a means for 3D design ideation in mixed reality environments. We developed and evaluated an interactive shape modeling mechanism that facilitates conceptualization of ideas using curve networks during early stages of design ideation. Our analysis shows that there are clear differences between user motor strategies for interactions with and without physical objects as stimuli. More importantly, we believe that future design tools using mixed reality should likely combine high-fidelity physics models for haptics along with direct physical feedback for better perceptual integration. Our work opens up a new direction in MR-based design using physical-digital kinesthetic feedback that can significantly augment the current MR technologies focused on visual integration of physical and digital spaces.

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