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Investigating Force-Feedback in Mid-Air Sketching of Multi-Planar Three-Dimensional Curve-Soups

In this paper, we report on our investigation of haptics-enabled mid-air interactions for sketching three-dimensional (3D) curve-soups—collections of three-dimensional multi-planar curves. We study pen-based mid-air interactions for free-form curve input from the perspective of manual labor, controllability, and kinesthetic feedback. We specifically study the role of kinesthetic feedback for two aspects of mid-air sketching, namely, drawing curves on planar surfaces and spatial rotation of 3D curve-soups. For this, we implemented a simple haptics-enabled workflow for users to draw and compose collections of planar curves on a force-enabled virtual canvas. The qualitative and quantitative analyses of our study-tasks show that there is a rich interaction design space of kinesthetic feedback methods for mid-air sketching beyond physically currently prevalent models.
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1 Introduction

Sketching plays an important role in embodying *controlled vagueness* [1] that is essential for the users to quickly externalize their ideas during design conceptualization. To date, the most successful digital sketching workflows are predominantly implemented using multi-touch interactions on tablets for the simple reason that they preserve the experience offered by the pen-and-paper medium, thus significantly reducing the interface learning curve for a novice user.

With recent advances in augmented and virtual reality and computer vision technologies, there is a significant interest in expanding the scope of sketching from two-dimensional (2D) media to three-dimensional (3D) spaces. At the same time, it is also argued [2] that sketching 2D representations of 3D ideas adds to the cognitive load, especially for novice designers leading to sketch inhibition. While this view is echoed by the existing interaction design research [3,5–] as well, little is understood regarding the underlying principles of interaction design for mid-air sketching interfaces. This is what drives our research motivating us to bridge the gap between the traditional sketching experience and pen-based mid-air interactions in virtual space.

In this paper, we build on our previously published work [6] and comprehensively investigate force-feedback algorithms in mid-air interactions for sketching 3D curve-soups. The motivation lies in capturing the physicality of sketching on paper, particularly in terms of how our physical drawing actions reflect the geometry of strokes being drawn. We extend this fundamental aspect of drawing curves to govern kinesthetically augmented mid-air interactions for 3D sketching. Our broader goals are to (a) understand the kinesthetics in sketching interactions so that they can be emulated in mid-air curve drawing, (b) understand the aspects of extending 3D manipulation interactions for 3D curve modeling, and (c) design interactions that integrate kinesthetics and information in user's mid-air actions with 3D curve modeling operations in virtual space.

1.1 Contributions. This paper extends and expands our recently published work [6], where we showcased a workflow for 3D curve modeling that (a) builds on existing spatial interactions and haptic approaches to create novel kinesthetic experiences for drawing in mid-air and (b) preserves controlled vagueness of sketching as an expressive medium for constraint-free externalization of ideas.

In this paper, we put forth three major extensions to our prior work [6], First, we conduct an in-depth investigation of planar force-feedback as means for providing controlled sketch strokes on the virtual canvas (Sec. 4.2). Second, we present a user evaluation to characterize the effect of our proposed force-feedback techniques for drawing different geometric curves (Sec. 6). Our evaluation helped us identify the three core aspects of mid-air interactions for curve-based modeling, namely, controllability, geometry, and perception. Finally, we characterize user behavior for 3D-curve modeling in terms of (a) effect of curve smoothness on kinesthetics for mid-air curve drawing, (b) continuity and controllability for drawing curves in a single stroke, and (c) user perception of modeling curves in virtual space (Sec. 6.4).

2 Related Work

Our work draws from several known interactive approaches for 3D sketching, mid-air interactions, and haptics. Below, we motivate and contrast our work with respect to relevant and related works.

2.1 Three-Dimensional Sketching on Tablets. There are two categories of approaches that address the creation of 3D sketches. The first category deals with the process of creating these sketches using tablet-based multi-touch interactions. In their work *ILoveSketch*, Bae et al. [7] introduced a comprehensive system for expert designers to create refined 3D sketches (curve-networks) for conceptualization. They further extended their approach to cater to novice

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users through their system *EveryodyLovesSketch* [8] using simplified interactions. In contrast, systems such as *MentalCanvas* by Dorsey et al. [9] allow for quicker creation of multi-planar curves that are more reminiscent of actual rough sketches primarily for architectural design conceptualization. The focus was on enabling architects to create 2D sketches for designing a building and later project each of these sketches in 3D space by controlling the position and orientation of individual strokes, thus creating a meaningful representation of the actual 3D idea. *SketchStudio* by Kim et al. [10] uses a similar projection-based approach for creating dynamic storyboards to describe 3D interaction scenarios by *fusing* multiple 2D sketches of the interaction elements (by position and orientation) into a 3D scene. Tsang et al. [11] demonstrated an adaptive design system that suggests reference images for the users to sketch upon based on curves drawn by the user, thus, providing intent-based visual cues for sketch-based design conceptualization. The *as-natural-as-possible* sketching experience works well in these approaches because of the tangibility and closeness to pen-and-paper sketching provided by stylus-based inputs to help the user create fine-quality 3D sketches. However, the key limitation in using tablets for drawing 3D curve networks is that there is no direct interaction for the user to access the third dimension (depth into and out of the screen). This limitation is usually addressed through patching up the interactive workflow using multi-touch or gestural inputs (e.g., two-finger pinch) that take time to learn and get used to for the user.

As an alternative to direct 3D input using a 2D interface (stylus-tablet), works such as *True2Form* by Xu et al. [12] automatically infer 3D curve networks from user-drawn 2D sketches through perceptually guided principles to estimate 3D curve-networks from their sketched 2D (projected) representations. Analogous to previously mentioned tablet-based systems, here the user sketches 2D representations of a 3D idea, but with the intent of helping the system understand and create a 3D curve projection out of it. This disparity between input and output interaction spaces adds to the user's cognitive load and may end up having the system to misinterpret the input sketch, eventually providing undesired 3D design outputs. While existing 3D sketching systems have shown promising results in helping with design ideation, there is a need for 3D design systems focused toward early design stages preserving the traditional user experience that captures pen-and-paper based sketching. Existing works showcase a feature-rich 3D sketching environment using multi-touch interfaces (both for novice and expert users); however, the non-intuitive mapping between 2D user input and 3D interactions add to the user's cognitive load requiring additional learning for the users [5]. Our work uses direct mid-air (spatial) input for creating curves in 3D space.

2.2 Three-Dimensional Sketching in Mid-air. The second class of 3D sketching research focuses on 3D user input [13–15]. One of the early works in this area is the *3-Draw* system by Sachs et al. [16] allowing *direct design in 3D* through intuitive creation and manipulation of 3D curves. Works such as *NapkinSketch* [17] and *Mobi3DSketch* [18] demonstrate novel systems for drawing multi-planar sketches in 3D space using a multi-touch device (tablets and mobile devices). In both cases, a hand-held device is used both as a frame of reference and an input canvas for creating meaningful 3D design concepts out of loosely connected multi-planar strokes in 3D space. While *NapkinSketch* uses a marker-based "napkin" as a reference in real world, *Mobi3DSketch* uses AR-enabled mobile devices for tracking the 3D space. These works demonstrate ubiquitous and portable 3D sketching systems limited to the creation of simple sketches in their early stages of development. In their work *Lift-Off*, Jackson et al. [19] propose a 3D modeling workflow to overcome issues with motion control and lack of initial reference for freehand modeling in VR-based systems. The interface uses 2D sketches as a reference to "lift" 3D curves from the sketch strokes to use them as a scaffold for creating surface models in VR. Addressing similar issues, few works have proposed hybrid design systems (2D multi-touch and 3D VR) [20–24] combining 2D and 3D input modalities for situated design tasks. Typical approaches involve either using mid-air gestures to create scaffolds that serve as a reference for sketching 3D design concepts or the user creates 2D sketches and uses gestures for manipulating 3D projections of the input sketches. One of the main issues in these works occurs due to the use of hand gestures that, while very effective for short interactions (such as object selection), lack the tangibility, and kinesthetic control is necessary for involved tasks such as concept sketching in mixed-reality systems [25]. Our work seeks to address this issue through the use of haptics within a mid-air sketching system.

2.3 Kinesthetics and Tangibility for Curve Modeling. Novice users find 3D interactions for sketching as intuitive and free, but lack of tangibility and depth perception adds to the user's cognitive load [26]. Several works have addressed this through specialized hardware (controllers and haptic-devices) either by adapting an application-specific sketching interaction into digital media [27] or by facilitating some form of controllability in mid-air interactions for design conceptualization [28]. Schkolne et al. [29] demonstrate a 3D drawing system that uses hand gesture along with physical tools for sketching and manipulating 3D surfaces. Through this work, the authors intend to provide the users with an intuitive perception of their actions and its relation to their interaction environment by using tangible media. Similarly, few works have investigated 3D curve(s) input using flexible physical proxies [30–32] such as bendable strips for mid-air curve and surface modeling. In addition to similar input and output interaction space, this approach provides a geometric mapping of the digital tool to its physical counterpart. The literature discussed in this section until now provide some form of tangibility for mid-air 3D modeling interactions; however, kinesthetic control is still a major shortcoming that has not been explored adequately. In their work *Artnova*, Foskey et al. [33] employed the haptic-based kinesthetic feedback for continuous indirect 3D object manipulation [33] in virtual sculpting tasks in a CAVE virtual reality systems. Here, the primary kinesthetic function provided by the haptic device was to sculpt an "existing" 3D model through a suction-based metaphor. Very few works have discussed kinesthetic feedback in the view of mid-air design conceptualization where the haptics involved are a simultaneous part of the user experience while sketching concepts from scratch, without the notion of an existing 3D artifact. Keefe et al. [28] demonstrated a haptics-enabled bi-manual interactive system for the controlled creation of 3D line illustrations in a virtual environment. The idea discusses a bi-manual approach where the user movement is constrained by an air-friction-based resistive force-feedback during the drawing of a free-form curve using a haptic device. Similarly, Raymaekers et al. [34] demonstrated a haptics-enabled sketching system for creation and modification of 3D curves represented as cubic Beziér splines. Here, the control points are responsible for an intuitive curve edition interaction using kinesthetic feedback. Also, Fünfzig et al. [35] demonstrated a haptic algorithm allowing the user to feel inflection points, cusps, and loops and use this intuitive feedback for deforming a curve naturally. In VR-based applications, it was observed that the stereoscopic vision is not, in itself, sufficient for depth perception in virtual systems and requires some tangible reaction force in the form of haptics. This view is also reciprocated by Massie [36] with the view of bridging the "disparity" between real and virtual worlds through physical interaction. While there is work on integrating haptics within sketching workflows, the interaction design space for kinesthetic feedback in sketching is quite rich and has not been explored in a comprehensive manner. In this work, we focus on systematically investigating kinesthetic feedback in mid-air sketching so as to provide guidelines for further research in this area.

2.4 Our Work. We aim to provide with a mid-air virtual drawing canvas that preserves the tangibility of physical pen-and-paper sketching experience. Prior works [37,38] have explored haptics on 2D interfaces for interactive purposes. Taking inspiration from existing works [34,39], we implement a multiplanar curve-modeling interface.

Our work is different from past works in two major ways. First, our interaction workflow is intended as a direct spatial extension to how one would produce a sketch on paper. Unlike earlier works, this extension is in the process of sketching (3D user input), the outcome of sketching (the 3D sketch), and the experience of sketching (perception of a piece of paper, but in 3D space). Second, our work adds to the existing body of work on 3D manipulation [40,41] in the context of curve modeling by decomposing the degrees-of-freedom (DoF) needed for curve creation and manipulation, respectively.

3 Overview

We define curve-soups as a spatial collection of planar curves residing on multiple canvas planes in 3D virtual space. The canvas planes are configured relative to each other so as to provide an abstract visual representation of 3D solid objects (Figs. 1(*c*) and 1(*d*)). To enable curve-soup modeling, the fundamental requirement is for the users to be able to draw planar curves at any desired position and orientation in space. Drawing from the work by Jacob et al. [42], we identify that the process of creating 3D curve collections can be naturally segmented into three fundamental operations: drawing, rotation, and translation. Below, we elaborate on our experimental setup, the interaction workflow, and the software architecture to enable these sketching operations.

3.1 Experimental Setup. The experimental setup (Fig. 1(*a*)) is comprised of a display monitor that displays a virtual canvas for the users to draw planar curves on. Alongside, paired is a GeoMagic Touch 6 DoF haptics device that affords two capabilities: positioning and orienting the haptic stylus and interacting through buttons on them. Our aim is to emulate a pen-and-paper like sketching experience in virtual environments where the stylus is used for curve inputs by drawing on a virtual canvas floating in 3D space. In addition, the stylus is equipped with buttons mapped to different interactions embedded in the curve-soup modeling workflow.

3.2 Apparatus. Our setup (Fig. 2) is composed of an MSI Dominator GT72 laptop computer with Intel Core i7-6700HQ CPU (3.6 GHz, 16 GB GDDR5 RAM), running 64-bit Windows 10 Professional operating system with an NVIDIA GeForce GTX 1070M graphics card. Our curve-soup modeling application was developed in C++ with OpenGL Shading Language for rendering.

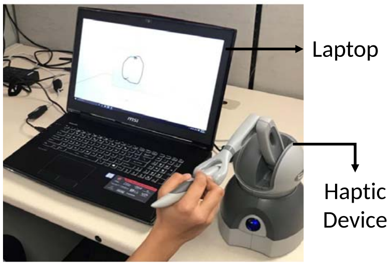

Fig. 2 Hardware setup comprising of display (laptop) and a 6DOF Geomagic Touch haptic device

3.3 Interaction Workflow. Our interaction workflow is composed of three operations [6]: (a) kinesthetic curve drawing, (b) canvas translation, and (c) curve-soup rotation, summarized as follows:

Kinesthetic Curve Drawing: We designed a haptics-enabled interaction wherein, given a fixed virtual canvas in 3D space, users could draw curves on it while experiencing a force-feedback against the stylus in the user's hand. This was achieved by providing a reaction force along the canvas normal (Fig. 4). Based on stylus proximity to the virtual canvas, a haptic feedback was activated attracting the stylus tip for sketching. Here, the user feels a spring force in a direction normal to the canvas with a magnitude proportional to the distance of stylus tip from the sketching canvas. The user can pull in and out of the canvas plane or move sideways to exit the sketching zone. Primarily, the user can start and stop sketching by staying out the boundary of the sketch plane. In addition, keyboard commands were assigned for redoing and undoing any drawn curve strokes.

Canvas Translation: We allowed translation of the virtual sketch canvas for positional control of the existing set of drawn curves in the scene. It served as an easy-to-understand interaction for new curve inputs by the users, without accidentally adding to an existing set of curves in the scene. To put canvas translation into effect, a user would press and drag the back button provided on the stylus. Here, the canvas was aligned parallel to the front (X–Y) plane of the global coordinate system. Being rigidly affixed to the stylus tip, allowed for the direct and proportional translation of the canvas. Arbitrarily oriented planes were not implemented due to

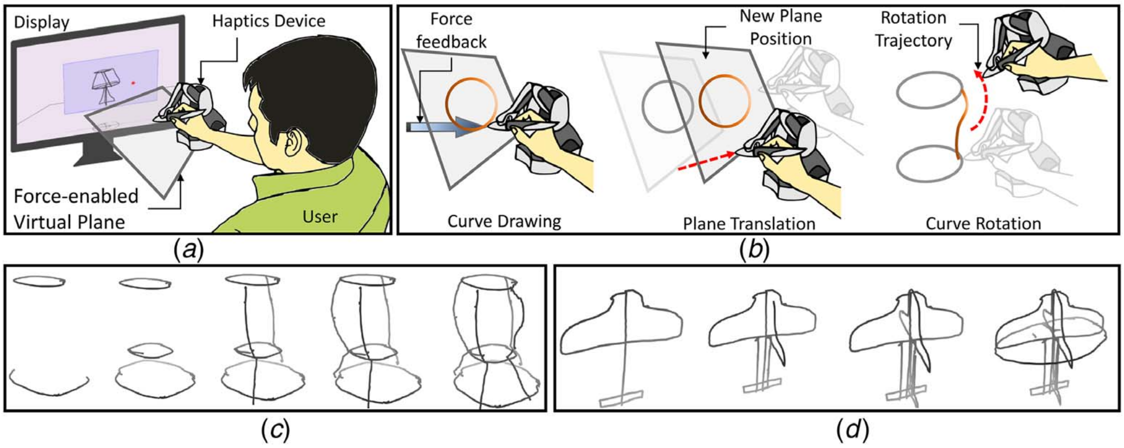

Fig. 1 General overview of the creative workflow and design representation: (*a*) user draws using a haptic device on a virtual plane in mid-air, which is rendered on the screen (system setup); (*b*) interaction workflow comprises of (C) *curve drawing*, (T) *translation* of sketch plane, and (R) 3D *curve rotation (interactions for curve-soup modeling);* and (*c*) and (*d*) user creates a multi-planar 3D curve-soup of a vase and a lamp using C, R, and T

limited range-of-motion of the haptic manipulator and incoherence of the visual feedback for the curves drawn on them.

Curve-Soup Rotation: We designed an interaction allowing the users to draw curves at desired relative orientations to each other. Here, the intention is for the users to rotate all existing curves in the scene at once about the global origin using the stylus trajectory. However, the choice of a single mid-air rotation scheme posed a challenge. In mouse or touch-based interactions [43,44], where the axis and angle of rotation is inferred through widgets such as arc-ball [45] or composed multi-touch inputs on the screen [46]. These ray-casting approaches have been extended to mid-air interactions by Katzakis et al. [47] in their *Mesh-Grab* and *Arc-Ball 3D* approaches. While these would work well for surfaces and solids, applying the same to curve is challenging merely by the attribute of the thickness (or the lack thereof) of curves and the resulting lack of precise controllability.

3.4 Software Architecture.

We classify our software architecture (Fig. 3) into four broad categories for processing the user input.

3.4.1 Range Normalization. By range normalization, we mean mapping the physical location of the haptic stylus to the openGL world coordinate system. Let $\mathbf{s}_t(x_t, y_t, z_t)$ represent the position of the haptic stylus at an instance t in the user's physical space. First, we determine the Cartesian coordinate axis (say A) along which the stylus has the maximum range of motion (this is needed to be done only once for the entire interaction). Let $[a_{\min}, a_{\max}]$ be the physical motion range, where $a_{\min}$ and $a_{\max}$ are minimum and maximum stylus motion range in centimeters along A. The normalized coordinates $\mathbf{v}_t(x_t, y_t, z_t)$ are given by

$$\mathbf{v}_t = -1 + \frac{2(\mathbf{v}_t - [a_{\min}, a_{\min}, a_{\min}]^T)}{a_{\max} - a_{\min}} \tag{1}$$

This effectively maps the physical range along coordinate axis A to the interval $[-1, 1]$, i.e., to the normalized device coordinates in OPENGL.

3.4.2 Trajectory Smoothing. The kinesthetic force-feedback algorithm directs the user toward the canvas from both directions along the canvas normal resulting on jerks in the user trajectory. To avoid jerks and accidental stroke inputs, we apply a low-pass filter to the stylus trajectory by using exponential smoothing [48,49]. Given a normalized point $\mathbf{v}_t(x_t, y_t, z_t)$ in the trajectory at instance t, the smooth coordinates $\hat{\mathbf{v}}_\mathbf{t}(\hat{x}_t, \hat{y}_t, \hat{z}_t)$ are given by

$$\hat{\mathbf{v}}_t = \alpha\mathbf{v}_t + (1 - \alpha)\hat{\mathbf{v}}_{t-1} \tag{2}$$

Here, $\alpha \in [0, 1]$ is the smoothing coefficient. We apply this process to all stylus trajectories across all three interfaces. As a consequence, the user experiences a smooth constant force (f) while sketching along the virtual canvas.

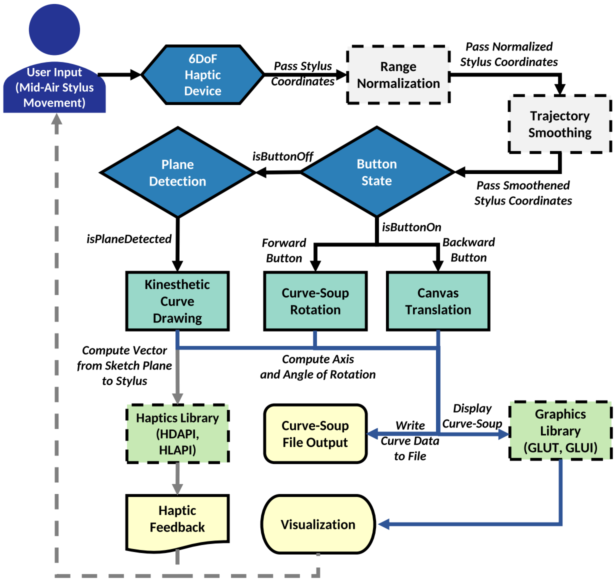

Fig. 3 Software architecture diagram for kinesthetically augmented mid-air sketching [6]

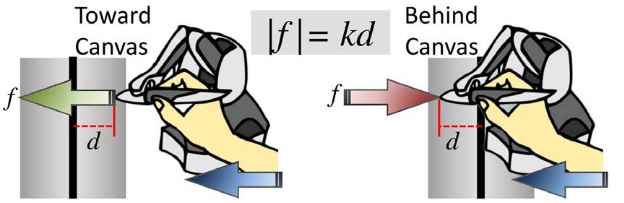

Fig. 4 Algorithm for proximity-based kinesthetic feedback for detection of drawing plane in mid-air [6]

3.4.3 Button Press. Our interaction workflow aims to provide a smooth transition across kinesthetic curve drawing, canvas translation, and curve-soup rotation interactions. Here, we used the two buttons (forward and backward) provided in the haptic stylus, forward button for rotating the 3D curve-soup and backward button to translate the drawing canvas. A user would press-and-drag the front and the back buttons, respectively, depending on the intended interaction. In our interface, *dragging* simply means moving in 3D space along an arbitrary path.

3.4.4 Plane Detection. In order to enable the kinesthetic drawing interaction, the user needs to be in the proximity of the virtual canvas within a pre-defined threshold distance $\boldsymbol{d}$. Within the threshold proximity, our plane-snapping method (Fig. 4) provides spring force-feedback to the stylus along with a visual cue that maps plane-stylus distance to the color intensity of the curve.

4 Methods and Tools

Below, we describe in detail the two main interactions that we studied in this paper.

4.1 Curve-Soup Rotation Technique.

We designed, implemented, and evaluated three rotation techniques for manipulating 3D curve-soups based on their degree of interaction directness. The intention was to reduce user efforts while increasing controllability for manipulating curve-soups in a virtual environment. We conducted a preliminary study [6] to evaluate the feasibility in terms of the above criteria for our proposed techniques. We have revised our analysis for better understanding of the problem described within the scope of this paper. In all cases, the idea is to compute an axis of rotation and an angle of rotation based on the 3D stylus trajectory.

G *Global Rotation:* Given two consecutive points $\mathbf{p}_i$ and $\mathbf{p}_{i-1}$ on the trajectory, the axis is computed as the normalized cross-product $\hat{\mathbf{a}} = \hat{\mathbf{p}}_{i-1} \times \hat{\mathbf{p}}_i$ and the angle is computed as $\theta = \arccos(\hat{\mathbf{p}}_{i-1} \cdot \hat{\mathbf{p}}_i)$ (Fig. 5(*a*)). This is, in spirit, similar to *Arc-Ball3D* proposed by Katzakis et al. [47] and most direct in terms of controllability compared with other techniques.

L *Local Rotation:* In this case, we used differential geometry to compute the axis and the angle. We consider the triangle formed by three consecutive points $\mathbf{p}_i$, $\mathbf{p}_{i-1}$, and $\mathbf{p}_{i-2}$ on the stylus trajectory. Subsequently, the axis is computed as the signed normal to the plane defined by this triangle, i.e., $\hat{\mathbf{a}} = \hat{\mathbf{v}}_1 \times \hat{\mathbf{v}}_2$, where $\mathbf{v}_1 = \mathbf{p}_{i-2} - \mathbf{p}_{i-1}$ and $\mathbf{v}_2 = \mathbf{p}_i - \mathbf{p}_{i-1}$ (Fig. 5(*b*)). In this case, we define the angle as $\theta = c\|\mathbf{p}_i -$

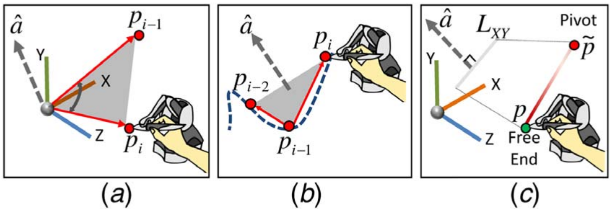

Fig. 5 (*a*) Axis and angle are computed about the global (G) origin, (*b*) axis and angle are computed using Local (L) stylus trajectory, and (c) axis and angle related to elastic (E) length of the line about a fixed pivot

$\mathbf{p}_{i-2}\|$. The constant c was determined through pilot experiments.

E *Elastic Rotation:* Absence of mouse or touch-based interactions leads to a lack of physical support in mid-air interactions. This leads to significant physical labor while interacting in a free-form manner. In this technique, the basic motivation was to create a continuous rotation of curve-soups through reduced user arm movement. Inspired by Knoedel and Hachet [46], we devised an indirect input approach wherein the rotation angle is mapped to stylus trajectory with respect to a fixed point. The press of the stylus button at a given *pivot* point in 3D space $\tilde{\mathbf{p}}$ fixes the point location. Further, for subsequent stylus trajectory $\mathbf{p}$, the orthogonal project of line $L(\mathbf{p}, \tilde{\mathbf{p}})$ on the X–Y plane forms the rotation axis $\hat{\mathbf{a}}$ such that $\hat{\mathbf{a}} \perp L_{XY}(\mathbf{p}, \tilde{\mathbf{p}})$. This indirect rotation interaction computes the angular velocity $\omega = b\|\mathbf{p}\tilde{\mathbf{p}}\|$. Perceptually, the interaction is analogous to stretching an elastic string, where the stretch length causes the curve-soups to rotate through continuously varying angles (Fig. 5(*c*)).

4.2 Kinesthetic Curve Drawing.

Our observations from the rotation focused study [6] inspired us to investigate further on the force-feedback for 3D curve inputs with the view of providing a continuous and controlled stroke input while sketching in mid-air. In this paper, we propose four novel plane force-feedback techniques focusing on enhancing user cognition and interactivity while drawing 3D curve-soups in mid-air. We conducted a user evaluation study to investigate which of our proposed techniques provide a feasible force-feedback.

We observed two main issues with our force-feedback algorithm for drawing on the canvas. First, proximal attraction to the canvas was found frustrating due to abrupt snapping motion while intending to draw curves. This caused unintentional strokes to be drawn on the canvas. Second, our restriction to draw planar curves in 3D took a while for users to get used to. This was due to the natural instinct of users habituated to create unrestricted non-planar curves in 3D space. However, the inherent problem of workspace limitation of the haptic device restricts the user movement beyond a certain degree-of-freedom. As currently, there are no untethered devices providing haptic feedback, this is a design trade off in our interface due to enable creation of curve-soup models. Our main goal in this paper is to resolve these two issues. Our first intention was to understand kinesthetic feedback for mid-air curve modeling and its relation to shape geometry. Subsequently, our aim was to explore kinesthetic interactions for controlled mid-air sketching of 3D curve-soups. Also, invoking a pen-and-paper based sketching experience through these interactions.

These observations strongly indicate that the users distinguished controllability into two broad categories: proximity-based stylus maneuvering in 3D space and consistent mid-air motion for drawing planar curves on the virtual canvas. In this stage, we design four novel force-feedback techniques to facilitate the aforementioned controllability.

We designed four distinct approaches to provide canvas force-feedback for 3D curve modeling. In all cases, the idea is to detect the user proximity near the virtual canvas, allowing the users to draw curves in a controlled and consistent manner. Besides one, rest force-feedback techniques expand on some variant of the spring-based force-feedback (Fig. 4).

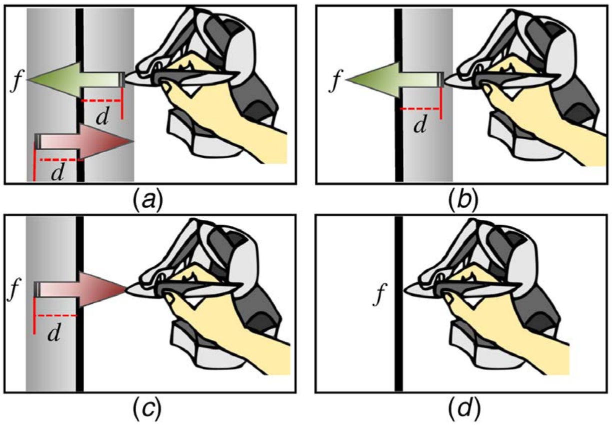

Fig. 6 (*a*)–(c) Proximity-based kinesthetic feedback for detection of drawing canvas in mid-air based on distance *d* from the plane and (*d*) constant force based virtual slate in mid-air

D *Double Suction:* Given a stylus tip point $\mathbf{p}_i$ is at a certain threshold distance d perpendicular to the vertical canvas. Based on this distance, the kinesthetic feedback provides a force attracting the user toward the plane (Fig. 6(*a*)). This resists any user movement away from the canvas in either direction through a *suction*-based metaphor. The suction force increases linearly with increasing distance d of the stylus tip away from the virtual canvas. The intention here is to provide a well-bounded detection zone minimizing any discontinuity of mid-air drawing interaction.

F *Forward Suction:* In this case, the suction force is unidirectional, i.e., kinesthetic feedback only attracts the user input before the plane (Fig. 6(*b*)). This implies lack of force-feedback for any user movement behind the canvas in 3D space. Thus, bounding the stylus tip to posterior proximity of the canvas.

B *Backward Suction:* Synonymous to **F**, the suction force here acts in single direction (Fig. 6(*c*)). The force being opposite in direction to **F**, kinesthetic feedback resists any movement beyond the canvas, restricting the stylus to the frontal proximity. Metaphorically, this feedback technique resembles a *tablet-like* sketching experience.

S *Slate:* In contrast to the aforementioned proximity-based force-feedback variants, this approach provides a constant force-feedback (Fig. 6(*d*)). This feedback technique was designed to provide a *chalk-and-slate* like experience while sketching on the virtual canvas.

5 Experiments and Results: Mid-Air Rotation

We conducted a preliminary experiment to evaluate the three rotation techniques (*Global* **G**, *Local* **L**, *Elastic* **E**) based on curve drawing accuracy, rotation efforts, and controllability. The results and observations from this experiment led us to investigate further on kinesthetic feedback for 3D curve modeling which is discussed in this paper. In the paragraphs below, we will describe selective details of our prior work for the sake of completeness (see prior work [6] for a comprehensive analysis of this experiment).

5.1 Participants.

The participants group involved a mix of 18 (five female, 13 male) students (23–30 years old) from engineering, architecture, and visualization majors. Based on the demographics survey, the participants belonged to two categories: *experts* with extensive experience with 3D sketching and 3D modeling software, and *novices* having limited or no experience with either 3D sketching or modeling.

5.2 Procedure. Each session started with the general introduction of the haptic device and user interface, familiarizing the participants with the interface and interaction workflow (drawing, rotation, and translation) for creating a curve-soup. This was followed by an initial demographic questionnaire. The experiment subsequently consisted of the following tasks:

Practice: Participants began by creating a simple set of curves (such as a wire-frame model of a cube, a tree, etc.) for 5 minutes. We ensured that they used all three interaction modes during practice.

T1: Each participant was shown a target 3D mesh (cube or frustum) on the display. The task was to trace a 3D curve-soup along the edges of the given mesh using all three rotation techniques. Thus, a total of six trials (three each for cube and frustum) were performed per participant. This lasted for 15 minutes for all trials per rotation technique.

Participants were encouraged to use the rotation, translation, undo, and redo operations for accessing different faces.

T2: This was an open-ended task for testing preliminary potential of our workflow for a 3D curve modeling system. In this task, each participant created curve-soups representing either a lamp-shade or a vase using all three rotation techniques. Thus, creating three curve-models per participant. No references in the form of mesh models were provided, and participants were encouraged to use the interactions for sketching creative shapes. This task lasted 5–7 minutes per rotation technique.

Task-Load Index: After each trial in **T1**, we recorded participants feedback using the NASA task-load index [50]. The questionnaire gauged the user response to mental effort, physical effort, annoyance, and similar performance-based attributes as described for this evaluation metric.

Questionnaire: On completion of the evaluation study, each participant responded to a questionnaire regarding the general interface features, use of haptic feedback during drawing, and a combined comparison of the three rotation techniques. Open-ended comments were collected regarding the overall interaction workflow.

5.3 Summary of Results. The following paragraphs briefly summarize observations that we have detailed in our prior work [6]:

Workflow, Rotation Techniques, and Visual Cues: We observed that the users with prior experience in 3D sketching and 3D modeling were trying to co-relate the rotation techniques to the ones available on the commercial 3D modeling software. This explains the discrepancy in user performance for Global and Elastic techniques for mesh tracing tasks. The users found it relatively easier to manipulate with the global and local techniques, owing to their direct input control algorithm. However, elastic technique was found to be relatively difficult to use by the participants due to its indirect nature for controlling rotation. Eventually, the users did prefer it cue for making fine rotations. One user intuitively mentioned, "*I can make finely control rotation to make detailed sketches to my design, which I am unable to do in Solidworks or any other CAD software*." Based on rotation techniques, the users came up with unique approach methods for creating the same open-ended curve-soup model across all interfaces. We observed that the order of the techniques affected the users' perception of the techniques. For instance, the users who began the trials with elastic technique faced an initial struggle due to the technique's indirect nature for rotation manipulation adding to their frustration. Although the users agreed that the elastic technique involved less physical effort, they gave higher importance to the directness of the interaction offered by the global approach.

The users made a considerable usage of visual cues provided by our interface across all three rotation techniques. Overall, the users were positive about shadows aiding as a depth cue while drawing multi-planar curves in 3D. Most users hinted at the presence of mesh models aiding their depth cues during the initial tasks. For the open-ended task, where no reference mesh model was provided, one user mentioned, *"Pretty easy to draw stuff with visual feedback. Everything becomes very difficult when there is no reference."* Another user mentioned, *"Shadows helped, but needed something else to understand where the sketching plane was.*" For the open-ended task (**T2**), both *novice* and *expert* participants were successfully able to sketch detailed wire-models of either a vase or a lamp shade effectively using the depth cues (Fig. 7).

Kinesthetic Feedback: The initial response for kinesthetically augmented 3D curve modeling was received positively (Fig. 8). However, few users found it difficult to acclimatize to the snapping metaphor for the rendering force on the virtual canvas. They were specifically frustrated during the plane detection phase from either direction. This, however, reduced with practice over time. Interestingly, we found that our force-feedback method also provided subtle depth cues to the users while drawing curves. One user said "Force feedback is a good indicator. It allowed me to sense where the sketch plane was in 3D space." While most participants could easily adapt to this interaction, a few participants (primarily from the *expert* category) mentioned the need for an explicit start-stop button.

6 Experiments and Results: Kinesthetic Drawing

The apparatus remained consistent across both the research stages for evaluation studies. However, we made two modifications to the interface. First, we introduced novel plane force-feedback techniques for drawing 3D curve-soups as discussed in Sec. 4.2.

In our prior work [6], the reason behind abrupt snapping of stylus to the virtual canvas was a consequence of sub-optimal spring constant value $\boldsymbol{k}$ and proximity distance $\mathbf{d}$. In order to mitigate this issue, we conducted preliminary experiments to find optimal $\boldsymbol{k}$ and $\mathbf{d}$ values for each force-feedback technique. Thus, the second modification involved adjusting the $\boldsymbol{k}$ value for each force-feedback variant to maintain consistency in haptic perception and controllability of sketching interaction on the virtual canvas.

Fig. 7 Curve-soup models for lamp-shade and vases created by the users during the open-ended task [6]

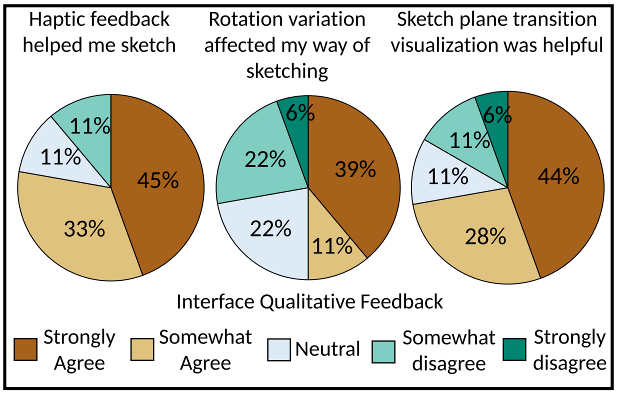

Fig. 8 Interface qualitative feedback interface kinesthetics, rotation techniques, and visual cues

6.1 Participants. The participant group involved a mix of 16 (five female, 11 male) graduate and undergraduate students (18–30 years old) from engineering, architecture, and visualization majors. Around 56% of the participants had preliminary experience in visual arts and 44% of the participants had hands on experience with 3D modeling software. This helped us gauge awareness of 3D sketching among participants. Similar to Sec. 5.1, we grouped the participants into *experts* and *novices* categories based on their experience with 3D sketching.

6.2 Procedure. In this study, we evaluate the four force-feedback techniques *Double Suction*(**D**), *Forward Suction*(**F**), *Backward Suction*(**B**), and *Slate*(**S**) based on curve drawing accuracy, drawing efforts, and controllability. For this study, the tasks were simpler compared with rotation-based tasks (Sec. 5.2). The intent here was the fundamental exploration of kinesthetic feedback for controlled and free-form mid-air sketching of 3D planar curves. The tasks were performed for all four force-feedback techniques (**D**, **F**, **B**, and **S**) in a randomized order using Latin square to account for learning biases.

The experiment took approximately 30 minutes. Each session started with the general introduction of the haptic device and user interface, familiarizing the participants with the interface for drawing multi-planar 3D curves. This was followed by an initial demographic questionnaire. The experiment subsequently consisted of the following task:

Practice: Participants began by creating a simple set of planar free-form curves on the canvas for 5 minutes. We ensured that adequate practice was provided for each feedback variant before starting with the trials.

Task: Each participant was shown a 2D shape wire-frame and asked to trace over it in a single stroke. With the intent to draw planar curves in 3D space, the tracing task helps us to quantitatively assess user performance in terms of shape accuracy and completion time for each force-feedback techniques. We chose square, circle, sinusoidal, and cusp as our target shapes (Fig. 9). Their geometric attribute of being C^2-continuous and piece-wise linear propose challenges single-stroke tracing action. Further, analogous to our prior work [6], these shapes varying curve smoothness. The idea was to provide cues for tracing and understand how kinesthetic feedback works with these commonly occurring geometric properties. While we did not have a rigid time duration for this task, we controlled each trial between 30 and 45 seconds. The target shapes were randomized using Latin square within each technique. A total of 768 trials were performed across all participants(192 trials per technique).

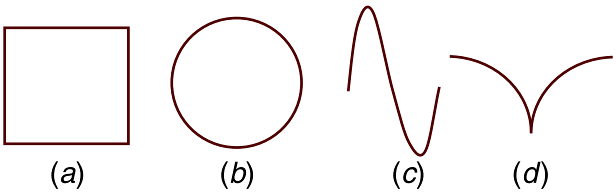

Fig. 9 Target 2D shape wire-frame with varying smoothness to be traced using for evaluating different canvas force-feedback techniques: (*a*) square, (*b*) circle, (*c*) sinusoidal, and (*d*) cusp

Task-Load Index and Questionnaire: After completion of trials for each feedback technique, we recorded participants feedback using the NASA task-load index [50]. Subsequently, each participant responded to a questionnaire regarding the general interface features, use of haptic feedback during drawing, and a combined comparison of the force-feedback techniques. We also collected open-ended comments regarding the overall experience of our interface and its value proposition.

6.3 Data and Metrics. For each trial performed by the participants, we recorded (a) the raw event log containing time-stamped stylus trajectory for each OPENGL frame, (b) the final 3D curve, (c) user feedback, and (d) live video of the participant.

For the task, our goal was to quantify the deviation of the user-generated curve with respect to the ground-truth, i.e., the edges of target shapes. For sketch-based accuracy evaluation, we used the root-mean-squared (RMS) error as described in our prior work [6].

6.4 Results. In the following sections, we report on the statistical analysis of the force-feedback techniques and discuss the main insights we gained from our data collection, observation, and user feedback from the trials performed by all participants.

6.4.1 User Performance—Drawing Accuracy. We make the following hypotheses here:

Null(H_o): There is no difference in mean RMS across all force-feedback variants for a given shape.

Alternate(H_a): There is a significant difference in mean RMS across all force-feedback variants for a given shape.

Another accompanying hypothesis is that the choice for a certain feedback variant differs with shape's smoothness, i.e., from piece-wise linear (e.g., a poly-line) to C^2-continuous geometries (e.g., sinusoidal curve). We performed the Shapiro–Wilk test on each data sample per shape per technique to check for normality (Fig. 10). Due to the deviation from the normal distribution, we further performed the non-parametric Kruskal–Wallis test for hypothesis testing based on the aforementioned null(H_o) and alternate(H_a) hypotheses. Statistical significance was observed for the square geometry confirming our alternate hypothesis **Ha**. Subsequently, the Dunn test was performed for a post-hoc analysis, and both **D** and **B** were found to perform better for the square tracing task (Fig. 10(*a*)). The box plot (Fig. 10(*a*)) shows **B** having a lower mean RMS error than **D**. However, most techniques showed similar mean RMS error for remaining geometries in our evaluation study, but a relatively lower minimum error was observed in approach **B** for the sinusoidal curve.

The above results confirm an important aspect of restricting the stylus tip to the frontal proximity of the sketching canvas in virtual space. Also, excerpting from the results for the square, we can generalize that piece-wise linear shapes are relatively difficult to be drawn in mid-air with continuity, consistency, and controllability.

6.4.2 User Performance—Completion Time. The participants showed complete effort in tracing the target planar shapes with a single stroke movement within the stipulated time per trial. Due to this task constraint, we observed a variation of completion

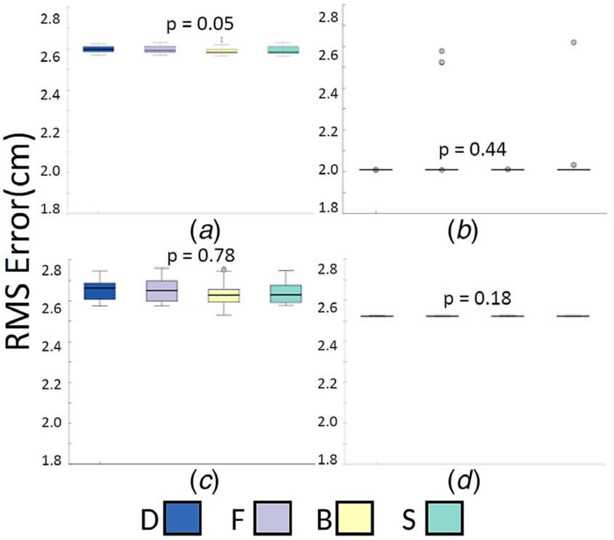

Fig. 10 RMS errors across force-feedback variants for (*a*) square, (*b*) circle, (*c*) sinusoidal, and (*d*) cusp shapes. Double suction (D) and backward suction (B) show lower mean RMS for square. Error bar for B shows a relatively lower minimum RMS than D. For circle and cusp, mean RMS and error range are similar across all techniques. Lower minimum RMS in variant B for sinusoidal geometry.

times across the different force-feedback techniques for a given geometry (Fig. 11). Here, we make the following hypotheses:

Null(H_o): There is no significant difference in mean completion time across all feedback variants for a given geometry.

Alternate(H_a): There is a significant difference across all feedback variants for a given geometry.

We also hypothesize that C^2 continuous shapes will take more time for tracing than the piece-wise linear shapes due to smoother curvature in the former. Analogous to the user performance evaluation, we performed the Shapiro–Wilk test for testing normality across each data sample per shape per technique. Each data sample was observed to deviate from a normal distribution. As a result, we performed the non-parametric Kruskal–Wallis test for hypothesis testing based on the aforementioned null(H_o) and alternate(H_a) hypothesis. Statistical significance was observed for circle, and a post-hoc analysis using Dunn test was performed (Fig. 11(*b*)) where forward suction **F** variant was observed to be relatively quicker in task response than other force-feedback variants and this can be attributed to easy detection of the sketch plane. However, the lack of consistency and controllability while performing the sketching task is observed in relatively higher RMS mean (Fig. 10). The performance across each feedback technique was similar for remaining geometries, but relatively lower range of completion time was observed for **D** and **B** variants.

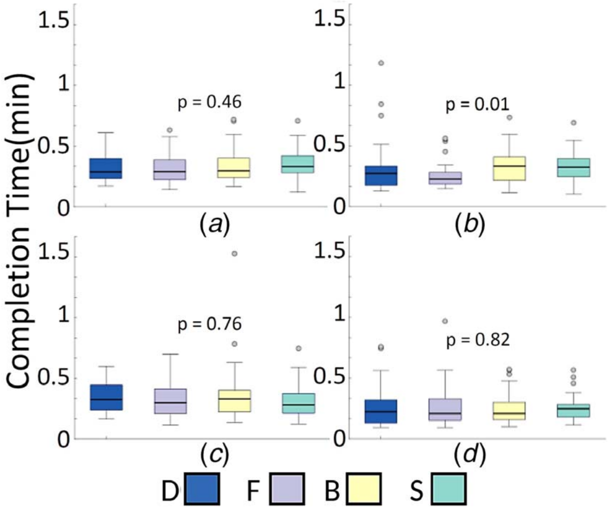

Fig. 11 Completion times across force-feedback variants for (*a*) square, (*b*) circle, (*c*) sinusoidal, and (*d*) cusp shapes. Forward suction (F) variant shows lower mean completion time for circle. Error bar for slate (S) variant shows a relatively lower minimum completion time. For square, circle, and cusp, error bars show lower completion time range for double suction (D) and backward suction (B) variants.

Borrowing from the results above, we can safely conclude the necessity of a consistent and controllable frontal proximity zone for sketching canvas which is provided by both **D** and **B** variants for most shapes. In addition, **D** serves as a suitable feedback variant providing additional support based on the smoothness of the shape to be sketched.

6.4.3 User Feedback and Observations. We collected open-ended user feedback post completion of trials for each feedback variant. Across 192 trials recorded for all participants, positive feedback was received toward the improvised proximity-based kinesthetic feedback around the sketch plane. Most users expressed comfort with the overall idea of modeling multi-planar 3D curves in mid-air using kinesthetic support. We discuss some insightful feedback in conjunction with our own observations during the tasks.

Canvas Force-feedback Techniques: Our primary goal was to evaluate the four force-feedback techniques. Users found the **D** and **B** techniques the most comfortable to use while drawing planar curves in mid-air. The common attribute here is the kinesthetic resistance provided beyond the canvas maintaining a consistent and controlled sketching interaction. One user intuitively mentioned, "*Staying in a given zone around the plane required less mental effort and I could draw easily without going too far in and out*." **F** was observed to allow relatively quicker and easy detection of sketching canvas. Its lack of kinesthetic feedback beyond the canvas caused repeated discontinuities in sketching action which annoyed most users.

On assessing the task-load index results, we observed double suction **D** technique requires least mental effort as per participants (Fig. 12(*c*)), whereas forward suction **F** technique was rated to be most mentally demanding. We collected responses for physical effort in terms of evaluation geometry—sharp and smooth curvature

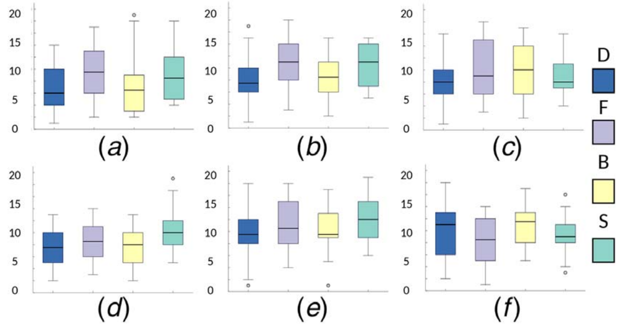

Fig. 12 (*a*)–(*c*) (0:low; 21:high): Qualitative feedback for the individual rotation techniques. (*d*,*e*) (0:easy; 21:difficult): Comparison of physical effort across all techniques for straight and smooth curves respectively. (*f*) (0:low; 21:high): Overall performance of force-feedback techniques. Double suction (D) technique preferred for lower annoyance, difficulty, mental and physical effort, and overall performance, closely followed by backward suction (B) technique. Slate (S) technique rated high for annoyance and physical effort. Forward suction (F) was rated the most difficult and least preferred overall: (*a*) annoyance, (*b*) difficulty, (*c*) mental effort, (*d*) effort-edge, (*e*) effort-curve, and (*f*) overall.

(Figs. 12(*d*) and 12(*e*)). Here, for both straight edges and smooth curves, technique **D** was found to be requiring least physical effort while drawing 3D curves (Figs. 12(*d*) and 12(*e*)) and technique **S** was found requiring most physical effort. In addition, for straight-edged geometries, backward suction **B** technique received equal preference as **D** for physical effort. Overall performance wise, user preference inclined toward both **D** and **B** techniques (Fig. 12(*f*)) and technique **F** was least preferred by the participants.

Sketching Workflow Evaluation: As observed in our prior work [6], users found it difficult to draw in a controllable and consistent manner on the virtual canvas. The two primary concerns discussed were stylus detection proximity around the sketching canvas and consistent sketching interaction for drawing 3D curve-soups. Our aim for the evaluation study in this paper was to take a step back and characterize kinesthetic feedback on the basis of curve geometry. Subsequently, iterate and select appropriate spring stiffness k value and proximity detection distance facilitating a smooth transition between idle and sketch modes. The users responded positively to the newly adjusted spring force and smoother interaction mode transition. As it is difficult to maintain a fixed position in mid-air, spring force supports the wavering motion along canvas normal while drawing planar curves. The *slate* inspired feedback was not received well due to its strong feedback and minimal proximity around the virtual canvas.

User Experience: Users with considerable exposure to 3D sketching could relate to direct implications of our proposition. Also, the ones with beginner experiences could look how mid-air curve modeling for spatially direct ideation would make a more natural extension of design expression. Thus, making the overall process of design cognitively less demanding. The cognitive load was reduced pertaining to stylus fall-out prevention beyond the sketch plane. In addition to users comparing our sketching interaction with traditional 3D modeling software, the kinesthetic feedback invoked a more fundamental perception of guidance-based controllability and navigation. One user stated,"*I found the experience similar to turning a car, how the steering returns back to a centered position after turning.*" At its core, kinesthetic feedback provided a fundamental insight on the simple task of creating curves in mid-air, which are the most fundamental geometric entities for any modeling interaction.

Fatigue: Each trial lasted for 30–45 seconds and 6 minutes per force-feedback technique. As a result, there was no prolonged mid-air suspension of the hand during the study and no complaints were received regarding physical fatigue by any participant. During the study, we advised participants to rest their hand between trials for each feedback technique. Also, the smooth sketching experience provided by proximity-based spring force diverted user focus from any fatigue. However, in case of *slate* technique **S**, users complained both about mental fatigue and physical fatigue due to simultaneous efforts of staying on a fixed plane while sketching on it.

7 Discussion

The results from our studies show that enabling mid-air sketching is not as straightforward as simply adding physically realistic haptic feedback to a spatial input device. Furthermore, creating such sketching systems for conceptual design add to the complexity because the design medium needs to be able to support the designer's creative processes. From this perspective, we made the following observations regarding the utility of mid-air sketching (as self-reported by participants), the role of force feedback on the virtual canvas, and the implications of our studies in relation to the general area of kinesthetic feedback for curve creation.

7.1 User Experience of Kinesthetic Mid-Air Sketching. We found the users to be in agreement with our original goal—preserving the essence of traditional sketching in mid-air interactions for design conceptualization. In particular, expert participants mentioned the potential for mid-air interactions to replace 2D sketches for design ideation. For example, one user aptly mentioned,"*As designers, we begin with concept generation using 2D sketches on a paper. Your system could allow us to ideate directly in 3D, providing more details about our design concepts.*" Another user mentioned, "*I am looking forward to such an application in future, making idea generation quicker and easier for us.*"

7.2 The Best Plane Force-Feedback Technique? Our primary goal was to allow for the users to create 3D curve-soups in a controllable and consistent manner. Serving the closest to our interaction requirements, we had a clear choice for the double suction **D** force-feedback technique. Though our preliminary evaluation for our prior work [6] implemented **D**, it used the basic idea of mitigating proximity-based detection problems. In our current work, we improvised on the fundamental attributes (spring constant **k** and proximity distance **d**) to overhaul the kinesthetic mid-air drawing experience. In addition to **D**, the backward suction **B** feedback technique fared close too for overall user preference. This puts forth the natural way to approach any canvas for sketching, i.e., from the front side. As **D** prevents stylus fallout from both directions, logically it confirms being the most suitable force-feedback technique for mid-air curve modeling.

7.3 Interaction Design Space for Kinesthetic Sketching. There is a rich space of unexplored kinesthetic interactions that are yet to be investigated for 3D sketching. For instance, extending the plane-snapping approach to 3D curves would enable to perform close-range operations such as curve refinement, deformation, and over-sketching [51]—operations that are common on tablets but extremely difficult in mid-air. Furthermore, such snapping would allow one to create topologically connected *curve-networks*, as opposed to curve-soups. Such curve-networks could be subsequently used for generating surface models [52].

8 Future Directions and Conclusions

While our primary goal was to enable new ways of mid-air sketching with kinesthetic feedback, this present work demonstrates that there are several fundamental research questions that need to be addressed before developing a complete sketching system for creative ideation. To this end, the current work specifically explored two basic interactions: rotation (which was investigated in our previous work [6]) and force-feedback methods for sketching on planar surfaces. Our study with planar force-feedback reveals two important aspects of mid-air sketching. First, the traditional view of providing a single static force-feedback is limited for proper controllability in drawing tasks. Second, the geometry of the curve being drawn affects the user performance and comfort. These two observations indicate a richer set of research directions to investigate and enable sketching on non-linear surfaces.

Our goal in the immediate future is to create a refined system for sketch-based design ideation, and our current findings will serve as the guidelines for designing the interactive workflow of such a sketching system. This future direction will focus on the evaluation of kinesthetic interaction workflow specifically for creative design. In the general area of haptics-enabled interactions, we want to understand how user perception and performance changes for basic manipulation tasks (rotation-translation-scaling) with and without haptic feedback. Finally, it will be interesting to see how we could extend our interaction workflow into a feature-rich 3D sketching system that allows for sketching on non-planar surfaces.

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