Kinesthetic Metaphors for Precise Spatial Manipulation: A Study of Object Rotation

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ABSTRACT

In this paper, we report on our investigation of kinesthetic feedback as a means to provide precision, accuracy, and mitigation of arm fatigue in spatial manipulation tasks. Most works on spatial manipulation discuss the use of haptics (kinesthetic/force and tactile) primarily as a means to offer physical realism in spatial user interfaces (SUIs). Our work offers a new perspective in terms of how force feedback can promote precise manipulations in spatial interactions to aid manual labour, controllability, and precision. To demonstrate this, we develop, implement, and evaluate three new haptics-enabled interaction techniques (kinesthetic metaphors) for precise rotation of 3D objects. The quantitative and qualitative analyses of experiments reveal that the addition of force-feedback improves precision for each of the rotation techniques. Self-reported user feedback further exposes a novel aspect of kinesthetic manipulation in its ability to mitigate arm fatigue for close-range spatial manipulation tasks.

1 Introduction

The commodification of augmented and virtual reality (AR/VR) systems has generated a significant amount of interest in the design of spatial user interfaces (SUIs). Consequently, much attention has been given to the design, development, and evaluation of spatial interaction techniques in AR/VR environments [1,2]. The fundamental premise underlying spatial manipulations is to embody our real-world experiences and interactions within virtual environments (VEs). The rationale is simple — virtual interactions that leverage our own physical experiences with manipulating objects will lead to better and effective interfaces for tasks that are inherently spatial. Such interfaces can be further effective in facilitating digital workflows involving the design and assembly of three-dimensional (3D) artifacts. As a result, XR systems (augmented-, virtual-, and mixed-reality systems) have tried to replicate the physical experience of object manipulation [3–7] within virtual worlds.

While physically realistic experiences, in principle, hold the promise of enabling intuitive workflows for 3D modeling and design, we argue that it is not physical realism *per se* but rather the augmentation of sensory perception and motor control that should drive the design of SUI. This view has been aptly echoed by Cipresso et al. [8] who state: "*The gap between the past and the future of AR and VR research is about the "realism" that was the key aspect in the past versus the "interaction" that is the key aspect now.*".

The fundamental premise of our work is that the true value of kinesthetic feedback is not merely as a simulator but as a facilitator that goes beyond the physical experience of forces and invokes the *perceptual quality of the physical experience*. As a case in point, consider how one rotates a physical object. The forces in play are typically friction between the hand and the surface and the object's weight. However, replicating this exactly does not necessarily facilitate precise rotation of a virtual object using spatial controller.

To demonstrate this point, we introduce three novel interaction techniques that allow users to precisely rotate 3D objects in virtual space through a 6 degrees-of-freedom (6-DoF) haptic stylus. We further investigate and compare these techniques in the context of precise rotational control of 3D virtual objects. An important aspect of our approach is that our interaction techniques are *metaphorical* rather than *literal*. This is inspired from works on non-physically realistic haptics [7, 9–13] that focus on using haptics to augment manipulation performance. The evaluation of these kinesthetic metaphors provides insight on fine motor control, physical and mental effort, and spatial exertion due to haptic assistance for precise spatial rotation tasks.

1.1 Contributions

We make three main contributions. Our first contribution is a set of three haptics-enabled interactions for precise rotation of 3D objects in virtual space. Second, we conduct a formal user-based evaluation of the rotation techniques to better understand (a) the advantages and disadvantages of force-feedback for fine spatial motor control in spatial manipulation and (b) how different interaction metaphors affect user approach, perception, experience, and overall performance in spatial rotation tasks. Finally, we provide a qualitative analysis to offer deeper insight on how haptics helps in mitigating fatigue and its effect on improving user performance for close-range high precision spatial manipulation tasks.

2 Related Works

2.1 3D Manipulation: Overview

Spatial interactions allow users to intuitively manipulate virtual 3D objects in SUIs. These approaches can be broadly classified as *real* and *magical* depending on the degree of replication of the true physical experience [14]. Both of these spatial manipulation approaches facilitate direct and indirect mapping of the physical user input allowing coarse and fine adjustment of the user input control. In their recent survey on 3D object manipulation approaches, Mendes et al. [15] put forth trends, analyses, design guidelines and challenges in existing 3D user interfaces stating, "*facilitation of effective manipulation for future 3D interfaces shall improve usability and adaptability of virtual systems*". This view is echoed in existing works focused towards the perceptual psychology of how users perceive virtual systems, their limitations, and learnability of different manipulation interactions [16]. One of the primary factors that governs the effectiveness of 3D object manipulation in SUIs is the type of input mode (2D or 3D). Prior works clearly show that 2D input modes, for example, using a mouse for spatial manipulation result in disruption of the visuo-motor space [17–19], creating a barrier for novice users to use virtual design applications. As a result, most interfaces that allow 3D manipulation using 2D input devices separate the rotational and translational DoFs. For example, the *Arcball* technique proposed by Shoemake et al. [20] is one of the most commonly used methods that maps user input on the screen to rotate 3D objects. The users draw an arc as a 2D input whose curve geometry is mapped to an equivalent 3D rotation in the virtual world. A recent iteration of this idea by Katzakis et al. [21] extends the *Arcball* approach for remote 3D object manipulation i.e. 3D objects located further from maximum user hand distance, by leveraging the restricted range of motion in ray-casting techniques. In another approach proposed by Veit et al. [22, 23], the authors demonstrate a dynamic decomposition of the user's hand motion based on their DoF to perform spatial manipulation tasks. They suggest that decomposing the DoF based on the manipulation action helps improve user performance in terms of accuracy and time to complete a given object manipulation task. One of the early works by Masliah et al. [24] designed an evaluation metric to measure the DoF used for different spatial manipulation interactions. Further, drawing from the work by Jacob et al. [25], we identify that the process of 3D object manipulation can be naturally segmented into three fundamental operations: drawing, rotation, and translation. Lately, in their work *The Roly-Poly Mouse*, Perelman et al. [26] introduced a multi-purpose hemispherical mouse like device allowing both 2D and 3D interactions for translation, rotation, and rolling tasks through an adaptive DoF mechanism; ranging from simple pointing and selection tasks to complicated 3D manipulation interactions. While this mouse-based approach performed better than existing 3D input devices, the authors acknowledged the need for an on-demand DoF separation for better precise motor control that could have helped improve user performance.

Moving ahead of conventional 2D-input based desktop systems, till date, tablet devices serve as an effective and well-adapted input medium for 3D object manipulation [15] for a large variety of applications. In their works *IloveSketch* [27] and *EverybodyLovesSketch* [28], Bae et al. introduce a tablet based 3D sketch system using stylus as the sketch input medium. This system allows for the stylus to be used for creation as well as manipulation of the sketched 3D curves; gesture based stylus inputs activate the manipulation mode followed by *isomorphic mapping* i.e. direct mapping of user actions. Similar approach can be observed in existing works incorporating multi-touch user input for 3D manipulation [29–34].

2.2 Spatial Manipulation

In response to the 2D user input, mid-air (spatial) interactions provide a direct way of interacting in 3D space [1, 15, 16] for object manipulation. Such SUIs are often viewed in a broader lens of Natural User Interfaces (NUIs), which primarily leverage innate sensory perceptions such as haptic, kinesthetic, visual, auditory,.etc for directly interacting with 3D objects in a virtual space [35–38]. Alternatively, Fu et al., describe NUIs as hardware or software interfaces that leverage the *human capabilities* for spatial manipulation [39]. While most works under the umbrella of NUI and SUI discuss 3D manipulation in terms of object selection, deformation, and positioning; very little is known and explored about spatial rotation for object manipulation. One of the initial explorations by Song et al. [40] showcases a bi-manual approach for 3D object manipulation using a virtual handle bar as an *object-control metaphor*. A separated DoF approach for spatial manipulation allows independent translation and rotation actions, where the handle bar's longitudinal axis is the axis of rotation while performing the rotation action. While effective, the results indicate a higher dependency on visual feedback for performing the manipulation interactions; partly due to absence of a force-feedback in virtual 3D space. A similar DoF separation approach is showcased in *The Smart Pin*, where Caputo et al. [41] showcase a widget based uni-manual approach for spatial rotation. Here, a single metaphorical *pin* widget is used to perform positional, rotational, and dimensional scaling actions on a 3D object. One of the advantages of this technique is to overcome the motion constraints introduced by Song et al.'s bi-manual handle-bar approach. Recently, Kim et al. [42] demonstrated an adpative DoF system allowing user to constrain the input action DoF on-the-fly so as automatically switch between different manipualtion modes. This approach was statistically proven to perform better than the DoF separation approach as mentioned in earlier works in this section. Alternatively, Hayatpur et al. [43] showcased a scaffold based approach to perform constrained 3D object manipulation; where one can rotate or translate on a plane, along a ray or about a point based on the degree of precision and control desired by the user.

For all the benefits that spatial manipulation offers, it also suffers through a severe limitation — physical fatigue and tiring of upper limbs due to prolonged suspension. To remedy this, AR systems have used see-through displays for co-located object manipulation approach [44, 45], where the overlap of the visuo-motor space with the physical world creates a more intuitive and perceptible interaction environment. In their work *MixFab*, Weichel et al. [46] utilize a see-through display approach for personal fabrication such as spatially designing a pen stand using a physical pen as a reference. Despite the many studies on spatial manipulation, the central goal of integrating sensory perception and motor skills towards *controlled* spatial manipulation of virtual objects is far from what is possible to make future SUIs usable and useful.

2.3 Kinesthetic Support for Mid-Air Manipulation

For interactions involving controller-based user inputs, it is crucial to have a *perceptual relationship* between the structure of the device and the task performed [25]. While the controller may facilitate the necessary technological feasibility, it may lead to a constrained user action affecting user's action-perception and complex, and performance. On the other hand, the authors observe that an unconstrained perceptual coherence between the control structure of input device and the nature of the task leads to better user performance. This view is resounded in works discussing integration of kinesthetic feedback in graphical user interfaces (GUIs), improving user performance by reducing errors in selection based tasks [47, 48]. However, if the perceptual structure of the task doesn't align with that of the input device or if the input device is incapable of visually reproducing the user action, it disturbs the visuo-motor perception of the task, thus, affecting user performance. Extending on this principle of perceptual coherence and the introduction of the *Phantom Haptic Device* [49–51], newer works showcase user adaptability towards kinesthetic interfaces for object manipulation; primarily for shape modeling, sculpting, and painting where force-feedback in relation to the virtual object makes the interaction intuitive and easily perceptible [52, 53]. Further, novel kinesthetic metaphors have been developed for *mid-air haptic displays* in order to improve virtual design tasks using 6 DoF haptic devices [7, 9–13, 54]. Although widely used, the kinesthetic feedback explored until now is limited to linear actions like translation and scaling of 3D artifacts than rotation about any arbitrary axis. Therefore, for most rotational manipulation tasks, there is a huge dependency on visual cues and indicators.

Kinesthetic interfaces have also been viewed in the light of design ideation for early product design, even as a support tool for final design concepts [55]. Similarly, few works have explored kinesthetic feedback on a more fundamental level for early design i.e. freeform curve modeling and sketches for ideation purposes [54, 56]. However, analogous to past works, the kinesthetic feedback here is limited to the sketching action and not manipulation of the sketches. In another iteration, works by Song et al. [57, 58] showcase 3D object manipulation by directly interacting with a scaled up physical representation of the virtual object, and perform manipulation actions on it; which is reproduced and further post processed in the CAD application. Further, with focus on the rotation manipulation only, spherical devices have been used as an *off the shelf* ideas as direct manipulation input devices [26, 59]. As stated by Klemmer et al. [60] on the importance of the sense of embodiment for kinesthetic mid-air interactions, several works lately have put forth the idea of *learning through practice* for tangible VR interfaces [38, 61–67].

2.4 Our Work

Our work inspires from recent works [68, 69] that evaluate 6 DoF kinesthetic control for spatial manipulation actions. Our primary focus is to understand, explore, and evaluate the role of kinesthetic feedback for spatial rotation in virtual design applications. Our work differs from existing kinesthetic techniques and approaches in the sense of understanding how haptic feedback in tasks such as rotation effects user performance in terms of task accuracy, completion time, and amount of spatial movement. Furthermore, we also seek to understand in a qualitative sense, how users experience and perceive force feedback in rotation tasks.

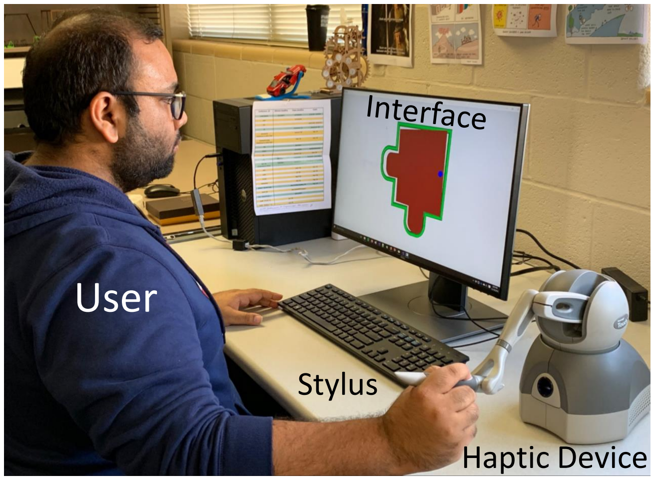

Fig. 1. User Experiment Setup for Kinesthetic Spatial Rotation.

3 Experimental Setup

In this section we provide a detailed description of our hardware setup, the need for kinesthetic feedback in spatial rotation, and the software architecture driving our rotation and kinesthetic feedback algorithms

3.1 Hardware

Our hardware setup (Fig. 1) includes a 3D Systems Geomagic Touch 6 DoF haptic device capable of providing a maximum force of 3.3N (0.75 lbf) rated by the manufacturer. The device consists of a hand-held stylus which we program to record 3D position, orientation of user input motion, and provide appropriate force-feedback, thus, facilitating kinesthetic spatial object manipulation. The rationale behind using a haptic-assisted stylus-like robotic-arm is the lack of availability of devices capable of providing a perceptible and configurable force-feedback alongside user-friendly APIs. Also, these devices have been used extensively for tasks such as 3D design [9–11, 54], surgery, and motor-rehabilitation [70] allowing to perform precise motor movements, which is the focus of our work. In our setup, the haptic device is connected to a display monitor for visualizing the spatial manipulation input actions in the VE. This setup is a close-range interaction volume allowing for users to spatially manipulate objects within an arm's distance from the user's body using the stylus. The stylus is also equipped with two programmable buttons, however, due to the nature of our experiment, only one is mapped to initiate the rotation interaction.

3.2 Force Feedback for Rotation

Prior works [22–25, 41, 42] have discussed the DoF decomposition of user spatial input resulting in improved user performance. The advantage here is that this interaction methodology is simple and focused on identifying each manipulation mode as an independent entity. This can be found useful for spatial design applications having both the input and output interaction space in 3D. However, the absence of a tangible feedback in SUIs makes it a less preferred choice for spatial object manipulation tasks. Few reasons are lack of physical support akin to 2D input medium such as tablet devices, fatigue due to prolonged mid-air suspension, and increased mental load due to action-reaction perceptual mismatch for virtual tasks. Hence, taking cues from interaction design and user-feedback in existing works (Section. 2), we understand the need to fundamentally generalize rotation in SUIs and further integrate kinesthetic feedback for an intuitive interaction approach.

We introduce and discuss three rotation algorithms in the perspective of kinesthetic feedback. While doing so, we also explore kinesthetic metaphors so as to find a *perceptual visuo-motor sweet spot* facilitating improved user performance and perception of the task performed in the VE. The underlying intention is to allow for the users to learn, understand, and explore through the three different kinesthetic metaphors for fine level spatial rotation manipulation with varying level of precision. The idea is that each of these rotation techniques shall invoke a novel kinesthetic experience for spatial rotation allowing users to make coarse and fine rotational manipulations on virtual 3D objects.

3.3 Software Architecture

We classify our software architecture (Figure. 2) into two broad categories for processing user input as follows:

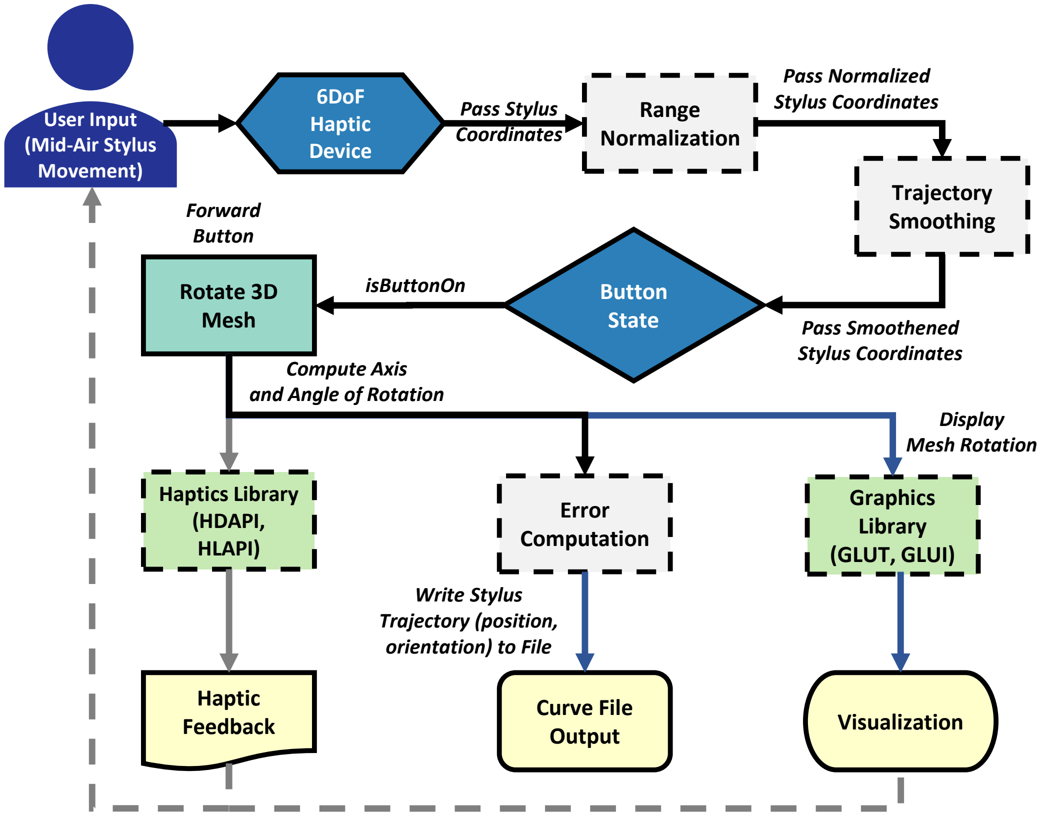

Fig. 2. Software Architecture Diagram for Performing Kinesthetic Spatial Rotation.

3.3.1 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.

3.3.2 Trajectory Smoothing

The kinesthetic force-feedback algorithm may result in unexpected jerks as observed through preliminary experiments. In order to avoid unintended rotational inputs, we apply a low-pass filter to the stylus trajectory by using exponential smoothing [71, 72]. 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 rotational techniques studied in this paper. As a consequence, the user experiences a smooth constant force (f) while rotating an object in 3D space.

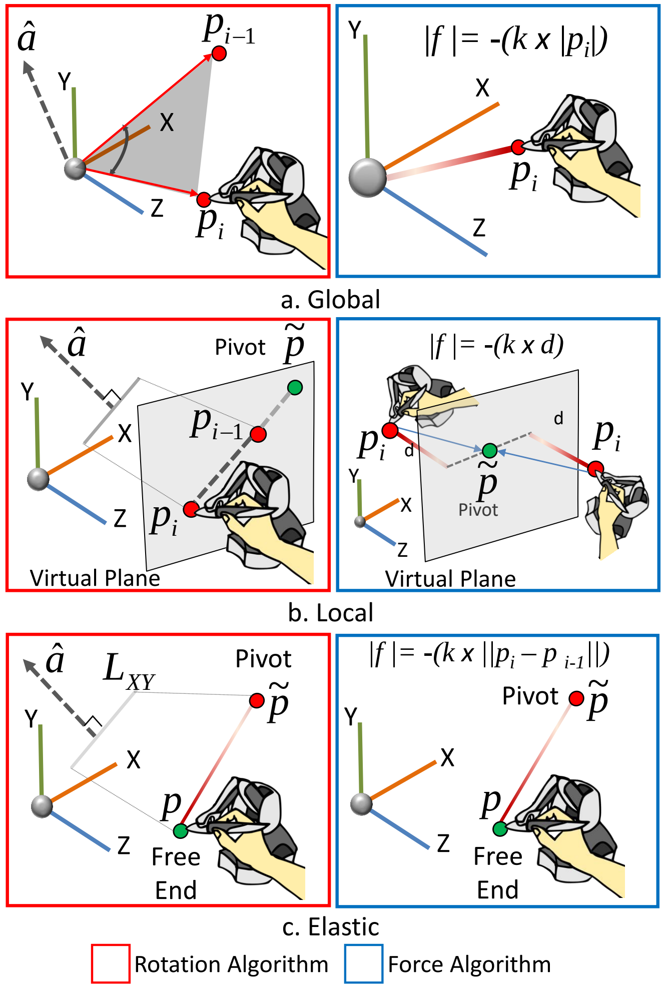

Fig. 3. Illustrations describing rotation algorithms and their corresponding force-feedback algorithms using 3D position and orientation data as recorded from the haptic device's stylus using the Openhaptics API. **Rotation Algorithm**: (a) Rotation axis and angle are computed about the origin of the Global (G) coordinate frame, (b) Rotation axis and angle are computed using Local (L) stylus trajectory, and (c) Rotation axis and angle are linearly related to Elastic (E) length of the line about a fixed pivot. **Kinesthetic Feedback Algorithm**: (a) Force feedback is a spring-based feedback pulling radially towards the origin of a **virtual sphere**, (b) Force feedback is a spring-based feedback along the line joining the stylus and its projection on the virtual plane (planar cushion), and (c) Force feedback is a spring-based feedback linearly proportional to the **elastic** length.

4 Methods and Tools

We designed, implemented, and evaluated three rotation techniques for 3D object manipulation. The intention was to reduce user efforts while increasing controllability for precise spatial object manipulation i.e the user should be able to make *fine rotations on demand*.

4.1 Global Rotation

4.1.1 Interaction Method

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 $\theta = \arccos(\hat{\mathbf{p}}_{i-1} \cdot \hat{\mathbf{p}}_i)$ (Figure. 3(a)). This is, in spirit, similar to *Arc-Ball3D* proposed by Katzakis et al. [21].

4.1.2 Force Feedback

Given the stylus co-ordinate $\mathbf{p}_i$ at a given instance of the rotation action, the feedback force experienced by the user is, $f = -(k \cdot |p_i|)$. Here, our intention is to provide a haptic feedback similar to a spring-mass system directed towards the origin of the virtual 3D scene; where the interaction space is limited to a virtual sphere with the radius continuously varying with the stylus position in 3D space. We found through preliminary studies that a stiffness value ($\mathbf{k}$) of 2 N/m provided a comfortable

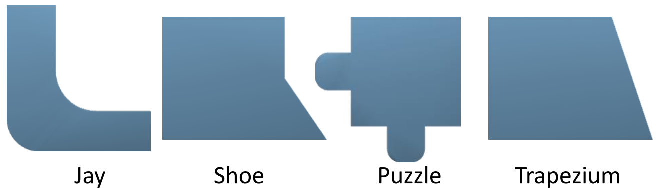

Fig. 4. Polygonal shapes used for evaluation tasks.

force feedback range for the Global rotation technique i.e. smooth and jitter-free perception of force feedback.

4.2 Linear Rotation

4.2.1 Interaction Method

In this technique, pressing the forward stylus button at a given point $\tilde{\mathbf{p}}$ in 3D space, establishes that point as the pivot. Further, a virtual plane containing $\tilde{\mathbf{p}}$ is established at a perpendicular distance $\tilde{\mathbf{d}}$ from the X-Y plane. For two consecutive stylus points $\mathbf{p_i}$ and $\mathbf{p_{i-1}}$, a line $L(p_i, p_{i-1})$ is projected orthogonally on the X-Y plane. The rotation axis $\hat{\mathbf{a}}$ is computed such that $\hat{\mathbf{a}} \perp L_{XY}(p_i, p_{i-1})$. In this case, we define the angle of rotation as $\theta = c\|p_i - p_{i-1}\|$ (Figure. 3(b)). The constant c was determined from pilot experiments.

4.2.2 Force Feedback

For a stylus point $\mathbf{p}_i$ in 3D space, its projection on the virtual X-Y plane is at a distance d_i from the stylus tip. This projection is at a distance $\tilde{\mathbf{d}}$ from the point $\tilde{\mathbf{p}}$ on the virtual plane. Taking an offset distance d between $\tilde{\mathbf{p}}$ and d_i, the feedback force is $f = -(kd)$. This resulted in a haptic feedback similar to a pillow cushion i.e. there existed an additional resistance along the Z-axis (along the length of the stylus), thus, allowing better spatial stability of user input trajectory on the virtual plane. Our preliminary studies showed that a stiffness value (**k**) of 7.5 N/m provided a comfortable force feedback for the Linear rotation technique.

4.3 Elastic Rotation

4.3.1 Interaction Method

In our third approach, the goal was to allow the users to perform quick rotation actions with minimal spatial effort. For this, we designed an *indirect* input methodology [31], where the stylus trajectory mapped to the rotational speed of a given 3D object. Here, on clicking the stylus button at a given point $\tilde{\mathbf{p}}$ in $3D$ space establishes the stylus position at that instance as the pivot point. Any subsequent point $\mathbf{p}$ in the stylus trajectory forms a 3D line $L(p, \tilde{p})$, further projected orthogonal onto the X-Y plane. Subsequently, We compute the axis $\hat{\mathbf{a}}$ such that $\hat{\mathbf{a}} \perp L_{XY}(p, \tilde{p})$. Instead of directly computing the angle of rotation, we compute the angular velocity $\omega = b\|p\tilde{p}\|$ (Figure. 3(c)). This interaction results in an illusion of stretching an elastic string to perform rotation with varying speeds controlled by the amount of elastic deformation.

4.3.2 Force Feedback

In this approach, there is a direct (metaphorical and physical) relation between the interaction and force algorithm. Owing to the notion of elasticity, we calculate the elastic force $f = -(k\|p_i - \tilde{p}\|)$ for providing a direct perception of elasticity in a virtual environment. A stiffness value (**k**) of 3.2 N/m provided a comfortable force feedback range preserving the elastic perception in the current rotation technique.

5 Experiment

5.1 Implementation

Our hardware (Figure.1) comprises of a Dell Precision 3620 desktop computer with Intel Xeon CPU (3.5GHz), 32GB of GDDR4 RAM, and a NVIDIA Quadro P2000 graphics card, running 64 bit Windows 10 Professional Operating System. Our 3D modeling application was developed in C++ with OpenGL Shading Language for rendering.

5.2 Participants

The participants group involved a mix of 34 (9 female, 25 male) students (18 - 30 years old) from engineering, architecture, and visualization majors. Our study was a *within subjects* experiment [73] evaluating the rotation techniques between two

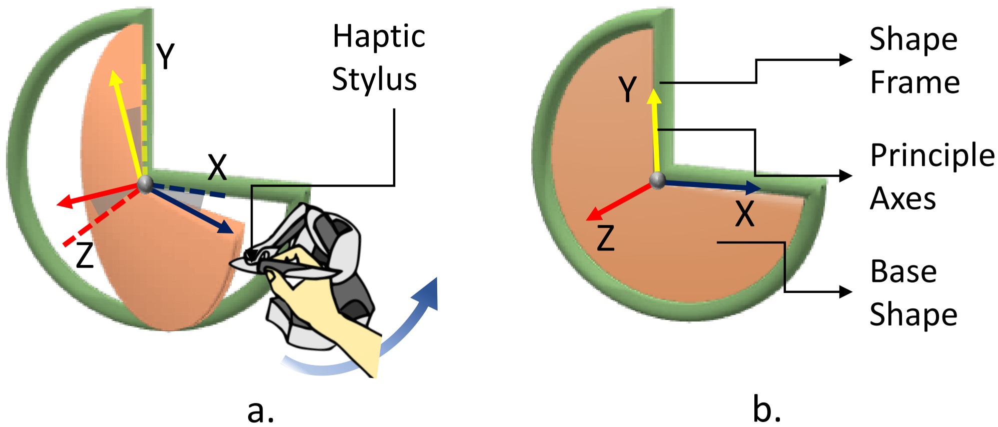

Fig. 5. (a) Default user-controlled interaction state with misaligned base shape, (b) Expected final state where the base and target shapes are aligned along their orientation vectors.

independent experimental control groups — precise rotation manipualtion *with and without force feedback*. This *between-groups* (haptics vs. non-haptics) and *within-subjects* experiment was designed with the intent of mitigating learnability [74] between the control groups as well as the three rotation techniques.

5.3 Evaluation Tasks

Our evaluation tasks were designed with three goals in mind: (a) to evaluate individual rotation techniques based on presence and absence of a haptic feedback, (b) based on first goal, we wanted to compare the rotation techniques for user performance, preferences, and behaviour for spatial 3D object rotation, (c) finally, we also wanted to observe user adaptability towards kinesthetic support for fine spatial motor control. Based on these goals, we designed the following evaluation task for users to perform.

5.4 Procedure

Participants were shown a pair of shapes (Fig. 5) — a *base* shape and a *target* shape. Both shapes were centered at the origin of the global coordinate system (in the graphics scene). The target shape was designed as a *wire* (or a thick *outline*) version of the base shape and its orientation was set such that the normal to the plane containing the target shape was parallel to the global z-axis. The base shape was designed to be a thin sheet-like extruded shape whose boundary was identical to the target shape. At each user trial, the base shape was randomly oriented (with its center still fixed at the origin). To note, we didn't provide any visual cues such as orientation vectors or rotation pivots in the actual study interface, thus, allowing participants to perform rotational movements using proprioceptive and kinesthetic cues provided by each of the rotation techniques. We used this setup to measure user performance in terms of rotation accuracy, completion time, and task load for each of our rotation techniques. We chose four different shapes (Fig. 4) portraying absence of reflective symmetry along the principle axes. The shapes were designed using Solidworks CAD modeling software such that Shoe and Trapezium have G^0 geometric continuity with sharp edges only, whereas Jay and Puzzle have a combination of G^0 and higher order geometric continuities. The rationale for absence of reflective symmetry was to let each shape have one unique orientation at which it aligns with the target outline. The intent was that the unique alignment for each of the four shapes would provide an insight on user approach for final alignment stages of the base and target shapes using each of our designed rotation techniques. We did not impose a time limit for the any of the tasks in our study.

The experiment took approximately 60 minutes each across both rotation groups — with and without force feedback. Each session started with the general introduction of the kinesthetic system and the study interface, familiarizing the users with our proposed way of interacting with a 6DoF haptic device (Fig. 1). This was followed by an initial demographic questionnaire. The experiment subsequently consisted of the following tasks:

Practice: Participants began by practicing the rotation of a few primitive shape extrusions (such as square, triangle, three-quarter circle) for 5 minutes. We ensured that each rotation technique was practiced adequately before commencing with the actual study trials.

Alignment Task: The task for each participant was to re-orient the base shape to match the orientation of the target shape. Formally, the task was to rotate the base shape so as to closely align the base shape with the target shape aligning the x, y, and z axes.

A total 48 trials per rotation technique (12 per shape); 144 trials overall across all rotation techniques was performed

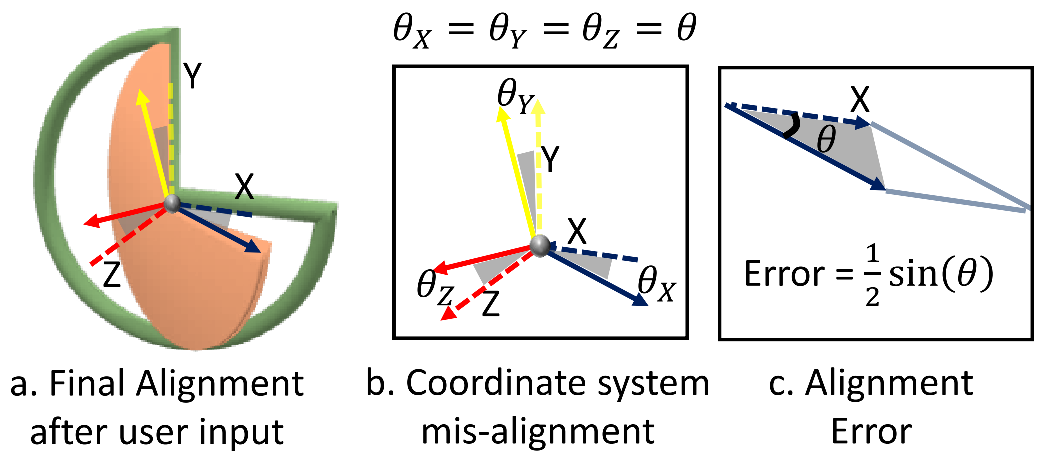

Fig. 6. Error metric for the rotation tasks performed by the users evaluating the misalignment error between the orientation vectors of the base and target shapes.

by each participant within the 60 minutes study duration. An identical approach was followed for the trials performed by the non-haptic feedback group. After each rotation technique, we recorded participant feedback using the NASA task-load index [75]. Each trial was randomized such that no two consecutive trial shapes were similar for a given rotation technique, therefore, the data per trial per rotation technique per control group performed by each participant was sampled independently. Subsequently, each participant responded to a questionnaire regarding the general interface features, overall spatial rotation experience, and a combined comparison of the three rotation techniques.

5.5 Data & Metrics

For each trial performed by a participant, we recorded the raw event log containing a time-stamped stylus trajectory where each stylus frame consists of the stylus 3D position, the orientation of the entire local coordinate frame of the base shape — shape being manipulated, and the button-press states on the haptic stylus (signifying whether the rotation was active or inactive). We additionally recorded the final orientation of the base shape, the user feedback provided through online questionnaires, and the participant video of them performing the spatial manipulation tasks.

In the rotation-based task, our goal was to quantify the misalignment error of user manipulated base shapes with their reference targets, i.e., the deviation between the orientation vectors of the user-controlled base shape and the corresponding frame axes of the final target frame. We have to come to realized that orientation error is a tricky concept to handle in 3D space. Direction vectors are parametrized through the unit sphere that has at least one singular point. What this further implies is that there are two angular variables (azimuth/elevation or latitude/longitude) whose statistical treatment requires directional statistics [76]. In this paper, we intended to simplify our analysis and wanted to consider a single numerical quantity to reflect the accuracy and precision of the rotation task.

Before choosing our final metric, we considered two different metrics. The first and simplest way to model error was be to directly measure angular deviation between the source and target orientation vectors (x-axis, y-axis, and the z-axis). However, from our analysis with the angle of deviation, we found that the data did not seem to follow any meaningful statistical behavior. There are two possible reasons for this. Theoretically, the angle of deviation is a derived entity measured derived from the more fundamental dot product. Second, the rotation of the object is performed by grabbing/clutching the base shape at some finite distance from the origin (as opposed to imagining a motor fixed at the origin). The second metric we considered was the dot product of the base and target orientation vectors. However, it has an inverse relationship to the error. Our final choice for measuring angular precision is one-half of the magnitude of the cross product (Fig. 6). The two reasons for this are: First, the cross product represents the signed area of the parallelogram formed by the base and target normals. Therefore, half of that magnitude provides a simple geometric measure that represents the minimum manual work needed to close the angular gap between the base and target orientation vectors. Secondly, it provides a theoretically sound way for avoiding the inverse relationship caused by the dot product alternative. In fact, it can simply be derived from the identity: $\cos^2\theta + \sin^2\theta = 1$. The alignment error is thus computed as (**Note:** While the result is a simplistic metric, this discussion is crucial and has often been missed in the statistical treatment of orientation data):

$$E_{deviation} = \frac{1}{2}\sin\theta \tag{3}$$

Here, θ is the angle between the orientation vectors of the base and target shape (that is the x-axis, y-axis, and the z-axis).

Shapes / p-value	Jay		Shoe		Puzzle		Trapezium	
	Haptics	Non-Haptics	Haptics	Non-Haptics	Haptics	Non-Haptics	Haptics	Non-Haptics
Error-X	0.91		0.52		0.16		0.37	
Error-Y	0.03		0.33		0.04		0.53	
Error-Z	0.19		0.48		0.46		0.32	
Compl. Time	< 0.001		< 0.001		< 0.001		< 0.001	
Path Length	< 0.001		0.003		0.05		< 0.001	

Fig. 7. Table describing p-values for a non-parametric two-way Friedman test comparing **between-subjects** (Haptics vs. Non-Haptics) and **within-techniques** (Global, Linear, and Elastic rotation) for each shape for error, completion time, and path length metrics. No statistical significance is observed for the two between-subjects group for error metric computed along each co-ordinate axis with regards to all shapes. Whereas, a statistically significant correlation is observed between the haptics and non-haptics independently sampled columns for completion time and path length metrics. However, Friedman's test doesn't share additional information on variability in mean differences along the rows, as well as, any interaction between rows and columns.

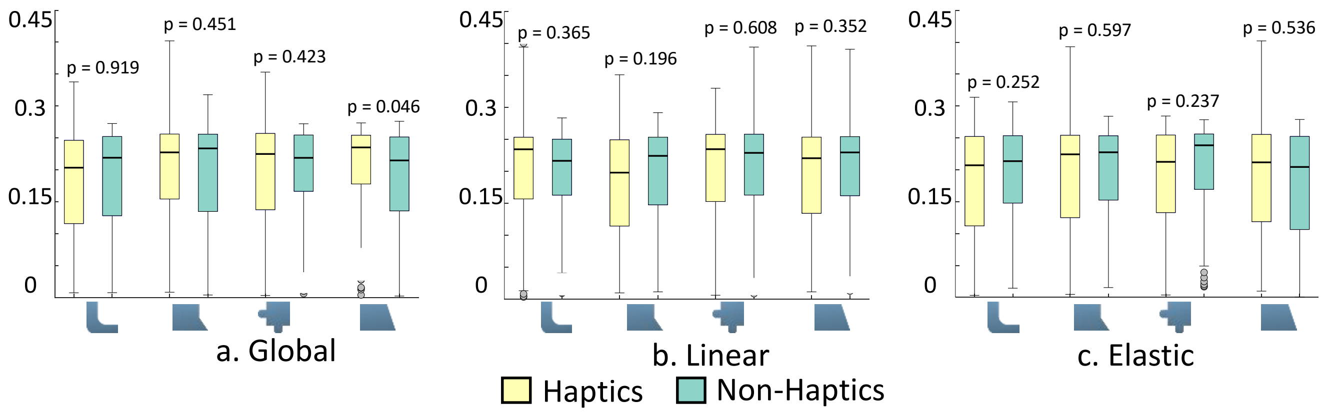

Fig. 8. (a,b,c) **Error comparison along the x-axis** between Haptic and Non-Haptic treatments for Jay, Shoe, Puzzle and Trapezium shapes using Global, Linear and Elastic rotation techniques.

6 Results

In the following sections, we report on the statistical analysis on comparison of the three rotation techniques — with and without the force feedback. Further, we discuss the main insights gained from our data collection, observation, and user-feedback from the trials performed by all participants. First, we present a two-way mixed-design comparison (section 6.2) between our experimental groups (Haptics vs. Non-Haptics) and within the rotation techniques (Global, Linear, and Elastic). Based on the results of the two-way comparison, we further present a pair-wise comparison of the haptic-based and non-haptics versions of each of the three rotation techniques (section 6.3). Finally, we shift our focus on comparing the three haptics-enabled rotation techniques for each of the four shapes (section 6.5).

6.1 Evaluating for Normal Distribution

Our first step was to verify if the data collected across all user trials is normally distributed. We evaluate the data samples collected from the haptic and non-haptic rotation groups using the Shapiro-Wilk test and normality is disregarded for p-values $<$ 0.05. For most data samples, we observed a non-normal distribution, hence, the following sections involve non-parametric hypothesis testing to verify statistical significance between the two control groups as well as within the three rotation techniques.

6.2 Two-way Mixed-Design Comparison

The *between-subjects* and *within-techniques* nature of our study necessitates to conduct a two-way mixed-design comparison to evaluate the variability due the differences among column (haptics vs non-haptics) means. For this, we choose the Friedman's test, which is the non-parametric equivalent of a Two-Way Mixed Design ANOVA test. We test for the following hypotheses,

Null(H_o): There is no significant difference between the independent factors (haptics vs. non-haptics) for a given user evaluation metric.

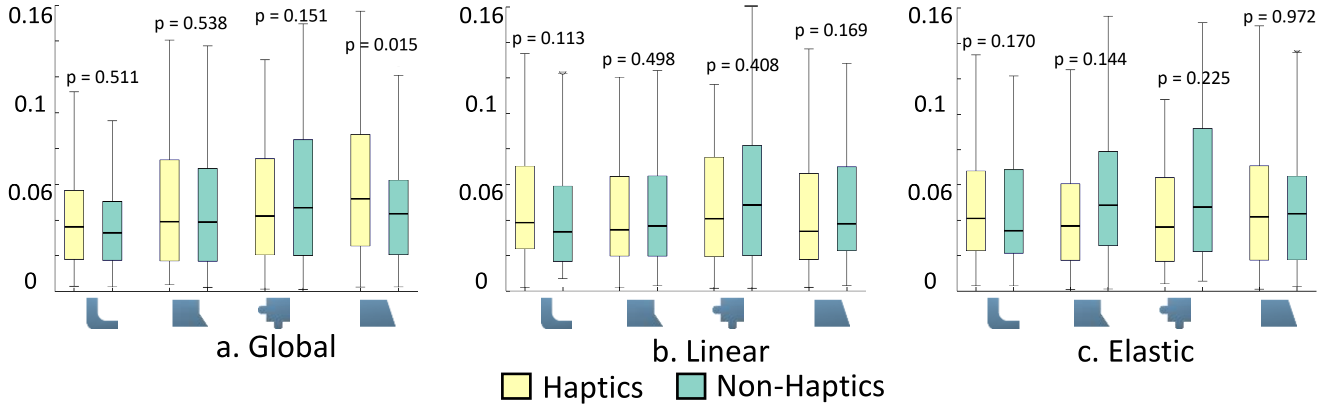

Fig. 9. (a,b,c)**Error comparison along the y-axis** between Haptic and Non-Haptic treatments for Jay, Shoe, Puzzle and Trapezium shapes using Global, Linear and Elastic rotation techniques.

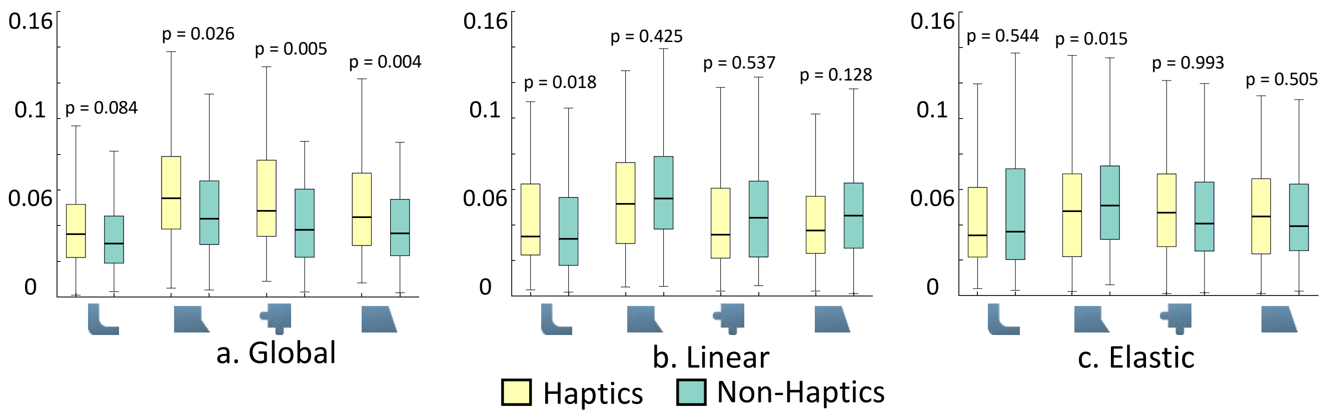

Fig. 10. (a,b,c) **Error comparison along the z-axis** between Haptic and Non-Haptic treatments for Jay, Shoe, Puzzle and Trapezium shapes using Global, Linear and Elastic rotation techniques.

Alternate(H_a): There is a significant difference between the independent factors (haptics vs. non-haptics) for a given user evaluation metric.

We conduct this column-wise comparison for misalignment error, task completion time, and overall total path length of the stylus trajectory while aligning the base and target shapes. As per our statistical analysis (Fig. 7), we observe no statistical significance for the misalignment error data for all shapes along each coordinate axis. Whereas, a statistical significance is observed for the task completion time, and stylus path length. The non-parametric nature of the Friedman's test doesn't allow for multi-comparison tests to evaluate variability in mean differences along the rows (rotation techniques), as well as, any interaction between the rows and columns (haptic treatments). Therefore, in the following section we conduct a non-parametric pair-wise comparison between the haptics and non-haptics variants of each rotation technique for a given shape.

6.3 Pair-wise Haptic vs. Non-Haptic Comparison

6.3.1 User Performance

Misalignment Error: Here, we evaluate the misalignment error along each axis (Figures. 8, 9, 10) and following are general hypotheses,

Null(H_o): There is no significant difference between the mean misalignment error along a given coordinate axis in presence and absence of haptic feedback for a given rotation technique.
Alternate(H_a): There is a significant difference between mean misalignment error along a given coordinate axis in presence and absence of haptic feedback for a given rotation technique.

We perform statistical analysis using the non-parametric Kruskal-Wallis test for hypothesis testing based on the aforementioned null(H_o) and alternate(H_a) hypotheses. Our observations for misalignment errors along each axis are as follows:

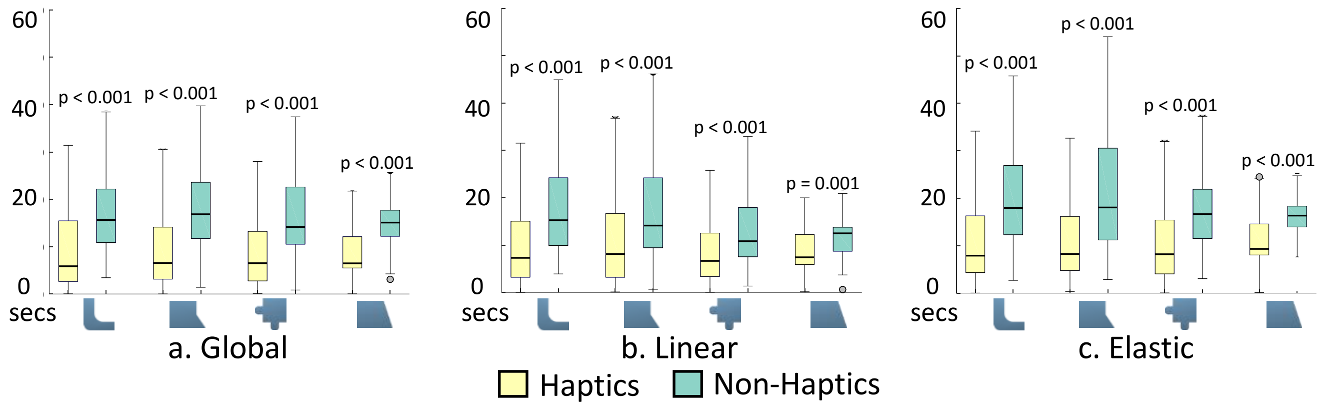

Fig. 11. (a,b,c) **Completion Time** comparison between Haptic and Non-Haptic feedback for Jay, Shoe, Puzzle and Trapezium shapes using Global, Linear and Elastic rotation techniques.

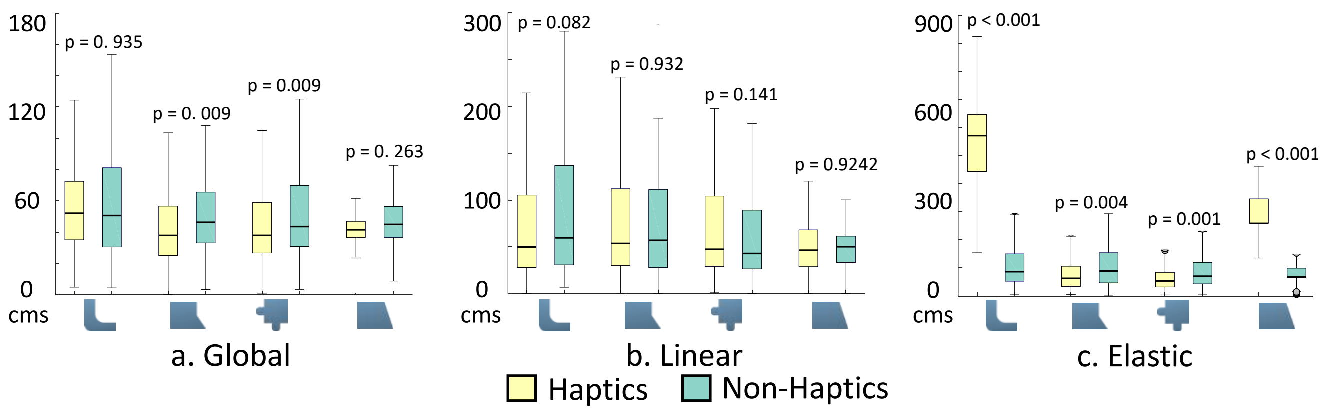

Fig. 12. (a,b,c) Total physical **Stylus Path Length** (in centimeters) covered across each trial between Haptic and Non-Haptic feedback for Jay, Shoe, Puzzle and Trapezium shapes using Global, Linear and Elastic rotation techniques.

***x*-axis:** We observe a significant difference in the misalignment error for the Global rotation technique for the Trapezium (p-value: 0.046) shape *favoring the non-haptic version*. However, no significant difference was observed between haptics and non-haptics versions of the rotation techniques across all shapes.

***y*-axis:** Similar to previous observation, we again observe a significant difference in the alignment error for the Global rotation technique for the Trapezium (p-value: 0.015) shape *favoring the non-haptic version*. However, no significant difference was observed between haptics and non-haptics versions of the rotation techniques across all shapes.

***z*-axis:** Here, we observe a significant difference in the alignment error for the Global rotation technique for Shoe (p-value: 0.026), Puzzle (p-value: 0.005), and Trapezium (p-value: 0.004) shapes confirming lower error values i.e. *better accuracy for the haptic variant of the rotation techniques*. However, no significant difference was observed for the Jay shape (p-value: 0.084). For Linear rotation method, significant difference was observed only for Jay shape variant (p-value: 0.018) *favoring the haptic variant*. For the Elastic technique, significant difference was observed for the Shoe shape variant (p-value: 0.015), *favoring the non-haptic version*.

Task Completion Time:

Null(H_o): There is no significant difference between the mean task completion times in presence and absence of haptic feedback for a given rotation technique.
Alternate(H_a): There is a significant difference between the mean task completion times in presence and absence of haptic feedback for a given rotation technique.

We perform Shapiro-Wilk test on each data sample measured for completion time per shape per rotation technique so as to check for normal distribution. Again, we perform the non-parametric Kruskal-Wallis test for hypothesis testing and observe (Figure. 11) an overall statistical significance (p-value $\leq$ 0.001) for all rotation techniques (Global, Linear, and Elastic) across

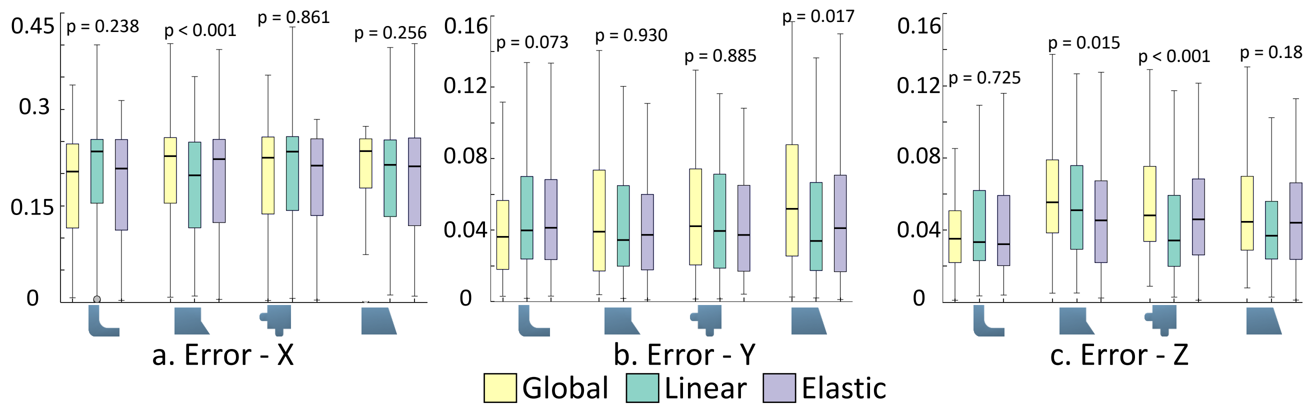

Fig. 13. **Alignment Error** along (a) x-axis, (b) y-axis, and (c) z-axis across Jay, Shoe, Puzzle and Trapezium shapes using kinesthetic variants of Global, Linear and Elastic rotation techniques.

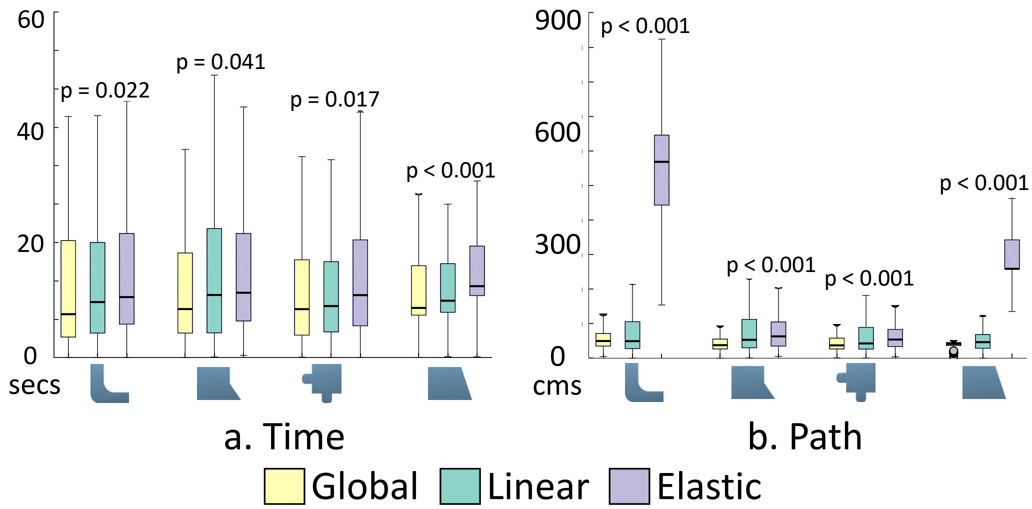

Fig. 14. (a) **Completion Time**, and (b) **Stylus Path Length** across Jay, Shoe, Puzzle and Trapezium shapes using kinesthetic variants of Global, Linear and Elastic rotation techniques.

all shape variants confirming a relatively shorter completion time compared to their non-haptic variants. The average task completion time using the Global haptic rotation was 8 seconds quicker than its non-haptic counterpart. Linear haptic and Elastic haptic rotation were 4.5 and 4.8 seconds quicker than their non-haptic counterparts respectively.

Stylus Path Length:

Null(H_o): There is no significant difference between mean stylus physical path length in presence and absence of haptic feedback for a given rotation technique.
Alternate(H_a): There is a significant difference between mean stylus physical path length in presence and absence of haptic feedback for a given rotation technique.

We observed statistical significance (Figure. 12) using Kruskal-Wallis hypothesis testing for Shoe (p-value: 0.009) and Puzzle (p-value: 0.009) shape variants with Global rotation while no statistical significance was observed for the Linear rotation. In case of Elastic rotation, overall statistical significance was observed across all shapes where most shapes had a p-value ≤ 0.001 except for Shoe shape with a p-value of 0.004.

6.4 Verdict: Is Haptics Better ?

On comparing our proposed rotation techniques across their haptic and non-haptic variants, the aforementioned statistical analysis present a fair assessment of kinesthetic feedback providing relatively better user performance in terms of rotation accuracy, shorter completion times, and lesser physical movement while operating the haptic stylus.

6.5 Comparison of Rotation Techniques

6.5.1 User Performance

In our earlier comparison between the haptic and non-haptic variants of the rotation techniques, we observed each data sample to be non-normal using the Shapiro-Wilk test. In this section we present a statistical comparison of only the haptic rotation techniques using the non-parametric Kruskal-Wallis test for hypothesis testing based on the null(H_o) and alternate(H_a) hypotheses stated for each of the following user performance evaluation metrics.

Alignment Error:

Null(H_o): There is no significant difference between mean misalignment error along a given coordinate axis across all rotation techniques for a given target shape.
Alternate(H_a): There is a significant difference between mean misalignment error along a given coordinate axis across all rotation techniques for a given target shape.

Our observations (Figure. 13) for misalignment errors along each axis are as follows:

x-**axis:** We observed statistical significance (Figure. 13(a)) across misalignment errors for the Shoe (p-value ≤ 0.015) shape, however, the same wasn't true for Jay, Puzzle, and Trapezium shapes. A post-hoc analysis on the Shoe shape using the multi-comparison test resulted in a significant p-value ≤ 0.001 for the comparison between Global and Elastic as well as Linear rotation techniques. Whereas, for Linear and Elastic rotation techniques, multi-comparison test resulted in a p-value of 0.83, which is insignificant.

y-**axis:** In this case, we observed statistical significance (Figure. 13(b)) across misalignment errors for the Trapezium (p-value = 0.017) shape, however, the same wasn't true for Jay, Shoe, and Puzzle shapes. A post-hoc analysis on the Trapezium shape using the multi-comparison test resulted in a significant p-value of 0.01 for the comparison between Global and Linear rotation techniques. Whereas, for Global compared with the Elastic rotation techniques resulted in a p-value of 0.09, which is insignificant. Similarly, there wasn't a significant difference between Linear and Elastic rotation techniques with a p-value of 0.79.

z-**axis:** We observed statistical significance (Figure. 13(c)) across alignment errors for the Shoe (p-value: 0.015) and Puzzle (p-value ≤ 0.001) shape variants, however, the same wasn't true for Jay and Trapezium shapes. A post-hoc analysis on the Shoe shape using the multi-comparison test resulted in a p-value of 0.009 for the comparison between Global and Elastic rotation techniques. Whereas, for Linear and Elastic rotation techniques, multi-comparison test resulted in a p-value of 0.0126 showing statistical significance. There wasn't any significant difference observed between Global and Linear rotation techniques for the Shoe shape variant, but they fared better than the Elastic rotation technique. In case of the Puzzle shape variant, multi-comparison test showed statistical significance for each pairwise comparison favoring the Global rotation technique with a p-value ≤ 0.001 in comparison to the Linear rotation technique. Similarly, comparison with the Elastic rotation technique resulted in a p-value of 0.012.

Completion Time:

Null(H_o): There is no significant difference between the mean completion times across all rotation techniques for a given target shape.
Alternate(H_a): There is a significant difference between the mean completion times across all rotation techniques for a given target shape.

We recorded overall statistical significance (Figure. 14(a)) across most shapes shapes with a p-value < 0.05 (Jay: 0.022, Shoe: 0.041, Puzzle: 0.017, Trapezium ≤ 0.001). Subsequently, the post-hoc analysis using the multi-comparison test resulted in the Global rotation technique being relatively quicker for Shoe (against Linear, p-value: 0.04; against Elastic, p-value: 0.006) and Trapezium (against Linear, p-value: 0.016; against Elastic, p-value ≤ 0.001) shape variants. For the Shoe shape variant, on average the haptic variant of the Global rotation technique was 2.9 and 4.83 seconds quicker than the Linear and Elastic rotation techniques respectively. In case of the Trapezium shape variant, on average the haptic variant of the Global rotation technique was 1.6 and 4.7 seconds quicker than the Linear and Elastic rotation techniques respectively. However, both Global and Linear rotation techniques fared similar for Jay (p-value: 0.123) and Puzzle (p-value: 0.250) shape variants, but quicker than the Elastic rotation technique for these shapes.

Stylus Path Length:

Null(H_o): There is no significant difference between stylus physical path length across all rotation techniques for a given target shape.

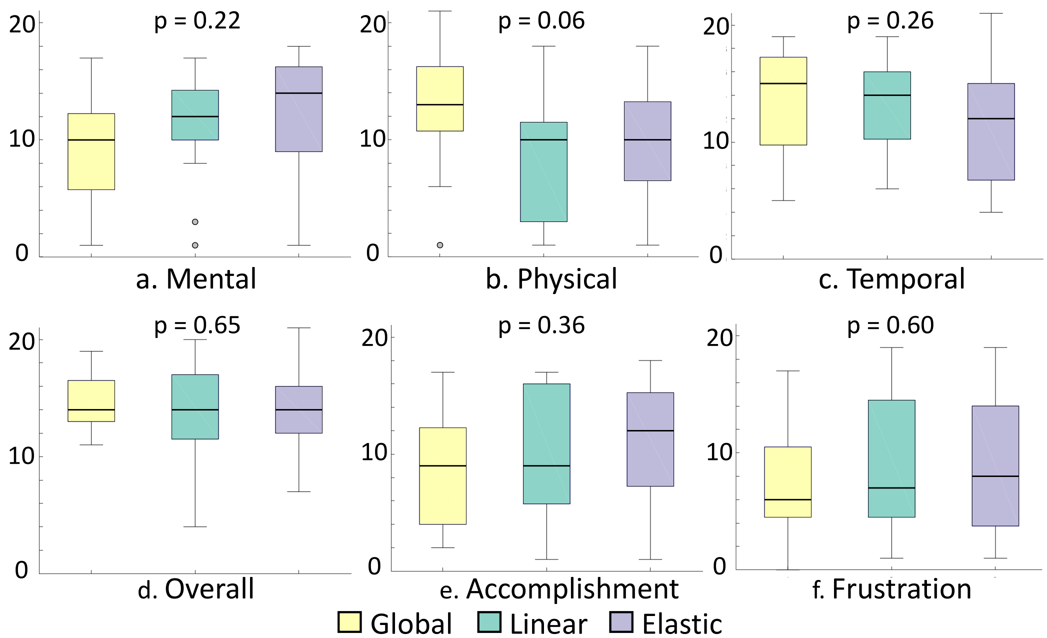

Fig. 15. Statistical comparison for user ratings across rotation techniques using NASA Task Load Index [1:low; 21:high]

Alternate(H_a): There is a significant difference between stylus physical path length across all rotation techniques for a given target shape.

We observed statistically significant differences (Figure. 14(b)) for Shoe, Puzzle, and Trapezium shape variants with p-values ≤ 0.001. A subsequent post-hoc analysis using the multi-comparison test showed that Global rotation required least spatial movement as compared to other two rotation techniques. For the Shoe shape, pairwise comparison against Linear rotation resulted in a p-value ≤ 0.001. Against Elastic rotation, the p-value was found ≤ 0.001. Further, for the Puzzle shape variant, pairwise comparison against Linear rotation resulted in a p-value of 0.006. Against Elastic rotation, the resulting p-value was found to be ≤ 0.001. Finally, for the Trapezium shape variant pairwise comparison against the Linear rotation technique resulted in a p-value of 0.002; against the Elastic rotation technique, the p-value is ≤ 0.001. In case of the Jay shape variant, Global and Linear rotation techniques (p-value: 0.404) required similar spatial movement, but relatively lesser than the Elastic rotation technique.

6.6 User Feedback & Observations

A total of 2448 trials were recorded across all participants for the haptic-based rotation techniques and an overall positive response was received towards kinesthetic support for spatial rotation actions. Most users expressed comfort with the overall idea of providing tangibility for spatial rotation to improve user performance and precise motor control. Below, we discuss user feedback in conjunction with our own observations during the tasks.

6.6.1 Global vs. Linear vs. Elastic Rotation

While the quantitative analysis clearly shows that the haptics-based methods resulted in better user performance (accuracy, time, and stylus path), the participants provided a mixed feedback putting forth interesting pros and cons for the haptics-based interactions. As a general consensus, haptic-enabled versions of Global and Elastic rotation techniques were perceived comfortable, intuitive, and easy to understand by majority of the participants. Although, the Linear technique fared well in the statistical analysis for few cases, it was perceived to be difficult from the point of view of user control and took some learning for the users to get accustomed to the rotation approach. One user intuitively mentioned,"*Global technique gave me a predictable mental mapping while rotating in 3D*". Similarly, another user found the Global rotation technique hands-on for coarse rotations due to its spherical rotation space, also, elastic rotation technique helped make finer rotational movements easy. Thus, the results and user feedback propose a possible combination of Global and Elastic rotation techniques enabling coarse and fine motor control for spatial rotation tasks.

Further, we conducted a statistical comparison using one-way ANOVA for the NASA task-load index results. Overall, no statistical significance was observed for each task-load index across the three rotation techniques, however, we made few significant observations. First, we observed that the Global rotation technique required least mental effort ($\mu = 9$) compared to remaining techniques (Figure 15(a)). On the other hand, despite receiving positive feedback for fine rotational movements, Elastic technique was rated to be most mentally demanding ($\mu = 12$) by the participants. This was attributed to the continuously varying axis of rotation making it difficult to predict the rotation axis as well as the direction of rotation of a virtual 3D object. On the other hand, akin to how one would perform precise rotational movements in the physical world using their wrist control, Global technique was rated higher for both physical ($\mu = 12.7$) and temporal effort ($\mu = 13.7$); this is due to one-to-one mapping of user action to the virtual 3D space. In the increasing order degree of user input control, Linear and Elastic techniques (Figure. 15(b)(c)) respectively rated lower in physical (Linear: $\mu = 8.5$; Elastic: $\mu = 9.8$) and temporal effort (Linear: $\mu = 13.2$; Elastic: $\mu = 11.4$) compared to Global rotation technique. As per overall algorithm performance and experience (Figure. 15(d)), Global rotational technique had a relatively higher average preference score ($\mu = 14.8$) from the participants. Also, it was rated relatively higher by the participants from the perspective of task accomplishment and less frustration (Figure. 15(e)(f)). In all, the three rotation techniques achieved more or less similar ratings, but Global rotation was more favored (least mental effort, higher overall performance, least accomplishment difficulty, least frustration) compared to Linear and Elastic techniques.

6.6.2 Force-feedback for Each Rotation

In the physical world, the tangibility for rotation manipulation is provided by the object itself through its weight, friction due to holding, etc. However, the absence of tangible feedback makes it perceptually and physically difficult to manipulate the object in 3D space. Generally, most discussed issues with spatial manipulation are controllability, accuracy, precision, and fatigue which are due to lack of haptic feedback in virtual world. In our study, haptics-enabled rotation received an overall positive feedback and was perceived as a much needed physical reference akin to the physical world that helps provide controllability and eventually improves spatial reasoning. While, spatial interactions are less preferred for its prolonged hover resulting in fatigue, kinesthetic feedback facilitates a supporting force mitigating the visuo-motor mismatch present in current spatial interactions. In our proposed kinesthetic rotation techniques, Global and Elastic rotation techniques encompass a spectrum of coarse and fine rotation movements respectively. The average forces for the Global rotation technique found across Jay, Shoe, Puzzle, and Trapezium shapes were between 0.1 N to 0.15 N. Whereas, for the Elastic rotation technique, the average forces across all shapes was found between 0.05 N to 0.1 N. The relatively lower force values is consequential to short bursts of elastic stretches performed by the user in order to make fine rotational motions to align the shapes. Similarly, the average forces for the Global rotation technique is consequential to the metaphorical interaction over a virtual sphere to make rotational movements, thus, aligning logically with their respective kinesthetic metaphors. While these forces seem to be low in a physical sense, previous works [77, 78] have discussed extensively about the quantitative and qualitative aspects of perceptible force-feedback by humans. These interesting observations motivate to further investigate interaction techniques that adapt to the user's need and shift between different rotation techniques providing an insight on an adaptive spatial rotation algorithm.

6.7 User Experience

In case of haptic feedback, most participants shared a positive experience and were generally more focused on the actual alignment task than controlling their hand movement in 3D space. On the other hand, for the non-haptic group, participants struggled to maintain a good balance between user input and the task input. This resulted in an extended mid-air hover leading to user complaints for fatigue. One user stated that "*Fine tuning was a problem*" and "*Holding the stylus for long hurt their hands*" in the non-haptic rotation variants. At its core, a more fundamental lack of additional support for precise control was observed in absence of an haptic-feedback which can be generalised for existing spatial manipulation techniques. Hence, there is fundamental need for exploring and characterizing kinesthetic rotation techniques and strategies for precise rotation manipulations.

6.8 Fatigue

One of the primary reasons for poor adaptability of SUIs is fatigue. One of the common examples of fatigue is the *Gorilla Arm Syndrome* [79–81] that characterizes physical exertion caused due to prolonged suspension of user hands in mid-air to perform spatial actions. While we did not conduct a quantitative assessment similar to *Consumed Endurance* [82, 83], the qualitative feedback collected from the participants provided interesting insight on the role of kinesthetic feedback for spatial manipulation. Most participants perceived the kinesthetic feedback as a resistive force providing a reaction to user's mid-air input action creating a virtual action-reaction pair. This helped the users utilize the force-feedback as physical support in 3D space allowing more precise control for fine rotation movements. While performing the evaluation tasks, none of the participants complained about experiencing any fatigue or exertion to their hands. One participant stated "*being involved in the task*" and didn't think about suspending their hand in mid-air until they were asked about it. Although qualitative, kinesthetic support for mid-air rotation did help mitigate fatigue making the input actions more intuitive, thus, keeping the users more involved in the actual task.

7 Discussion

7.1 User Experience for Kinesthetic 3D Manipulation

Our study has strong implications to the design of spatial user interfaces for design tasks that involve precise actions. Precise manipulations occur closer to the body — this is in fact the fundamental outcome of Gibson's well-known ecological psychology theory [84, 85]. Although, mid-air interactions levy the freedom to interact with close proximity to human body, the lack of a physical feedback makes it difficult to control the input actions. In our study, users were allowed to place the haptic device at a comfortable position and distance from their body. This is important because a comfortable arm posture helps reducing physical exertion which allows the users to shift their focus towards the manipulation task that requires fine motor control. On integrating kinesthetic feedback, however, we observed a much pronounced effect on accuracy and motor control. This can be explained in terms of the concept of coupling [86] — how humans can assume tools as a part of their own bodies and perform very finely controlled interactions with other objects. The second most critical outcome of our study is the observation that kinesthetic feedback provides a counter-balance effect through resistance of user motion. This allowed users to perform varying degree of precise manipulation with considerably lower physical and mental effort, as self-reported by the users themselves. Thus, it is important for haptic interfaces to accommodate both large-scale and nuanced user movements while providing a synonymous kinesthetic feedback, creating a synergistic action-perception pair for spatial manipulations.

7.2 The Best Kinesthetic Rotation Technique ?

The kinesthetic rotation techniques were designed and developed with precise manipulation as the primary motivation. In our work, we evaluated these techniques to rotate and align a base shape to its reference outline shape where the former was pivoted around its geometric center. There are other works that have explored pivoting and rotating the shape about its corner for spatial rotation tasks [87]. However, our interface didn't supplement the users with visual cues such as rotation axis and pivot, therefore, rotating a 3D object about its local orientation vectors pivoted at the geometric centre would be relatively intuitive and easy to interpret for our aligment task. In terms of *directness* of user input, each rotation algorithm adhered to spectrum of coarse and fine rotation manipulations. The Global rotation technique provided a direct mapping of user's physical movement to the virtual world. On the other hand, the Elastic approach was an indirect mapping, and the Linear technique falls somewhere in between the two. While the Elastic rotation version allowed fine rotational movements, its continuous nature made it was relatively difficult for the user to conceptually understand when compared to the Global approach. On the other hand, Global rotation obeyed to user movement and could be initiated and rotated to any position in 3D space on demand. While our study task was limited to rotating shapes pivoted at their geometric center, overall user feedback, and user experience favored the Kinesthetic Global Rotation technique.

7.3 Interaction Design Space for Kinesthetic Rotation

This paper presented three different kinesthetic metaphors for merely one spatial task — rotation. In rotation alone, there is a vast scope of exploration of even more interactions (such as adaptive force feedback based on the precision requirements or constrained rotations on planes and along individual axes) that need to be further investigated. Moving from rotation to translations can provide further avenues for the design of new spatial interactions. From a broader perspective, the idea of kinesthetic metaphors provides a rich space of unexplored kinesthetic interactions that are yet to be investigated for 3D rotation in conjunction with 3D translation. For instance, switching the kinesthetic feedback across different degrees of freedom (say from rotation to translation and vice-versa) is a potent research direction that has been surprisingly under-studied in literature. Studying the effect of kinesthetic constraints can provide valuable insights for the design of future spatial user interactions.

8 Future Directions and Conclusions

Our primary goal was to understand the role of kinesthetic feedback for spatial rotation. In this regard, this work demonstrates that there are several fundamental research questions that need to be addressed toward creating a kinesthetically supported 3D object manipulation system. The current work specifically explored: preference of haptic-feedback for mid-air rotation manipulation and preferred kinesthetic rotation technique for precise manipulation tasks. Our study reveals two important aspects of mid-air rotation. First, kinesthetic feedback, in general, makes a significant difference in terms of enabling precise motor control. Second, the presence of a physical support helps reduce cognitive mismatch and user hand fatigue for prolonged spatial manipulation tasks.

Our goal in the immediate future is to apply the insights gained in this study to further investigate a complete manipulation system that integrates both translation and rotation for spatial object manipulation. We aim to improve our understanding regarding how user perception and performance changes for basic manipulation tasks (rotation-translation-scaling) with and without haptic feedback. Finally, we seek to apply the new interactions techniques toward practical spatial applications for computer-aided geometric design.

9 List of Figure Captions

Acknowledgements

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