INVESTIGATING PRECISE CONTROL IN SPATIAL INTERACTIONS: PROXEMICS, KINESTHETICS, AND ANALYTICS

A Dissertation

by

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

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August 2021

Major Subject: Mechanical Engineering

ABSTRACT

Augmented and Virtual Reality (AR/VR) technologies have reshaped the way in which we perceive the virtual world. In fact, recent technological advancements provide experiences that make the physical and virtual worlds almost indistinguishable. However, the physical world affords subtle sensorimotor cues which we subconsciously utilize to perform simple and complex tasks in our daily lives. The lack of this affordance in existing AR/VR systems makes it difficult for their mainstream adoption over conventional $2D$ user interfaces. As a case in point, existing spatial user interfaces (SUI) lack the intuition to perform tasks in a manner that is perceptually familiar to the physical world. The broader goal of this dissertation lies in facilitating an intuitive spatial manipulation experience, specifically for motor control.

We begin by investigating the role of ***proximity*** to an action on precise motor control in spatial tasks. We do so by introducing a new SUI called the Clock-Maker's Work-Space (CMWS), with the goal of enabling precise actions close to the body, akin to the physical world. On evaluating our setup in comparison to conventional mixed-reality interfaces, we find CMWS to afford precise actions for bi-manual spatial tasks. We further compare our SUI with a physical manipulation task and observe similarities in user behaviour across both tasks.

We subsequently narrow our focus on studying precise spatial rotation. We utilize haptics, specifically force-feedback (***kinesthetics***) for augmenting fine motor control in spatial rotational task. By designing three kinesthetic rotation metaphors, we evaluate precise rotational control with and without haptic feedback for 3D shape manipulation. Our results show that haptics-based rotation algorithms allow for precise motor control in 3D space, also, help reduce hand fatigue.

In order to understand precise control in its truest form, we investigate orthopedic surgery training from the point of ***analyzing*** bone-drilling tasks. We designed a hybrid physical-virtual simulator for bone-drilling training and collected physical data for analyzing precise drilling action. We also developed a Laplacian based performance metric to help expert surgeons evaluate the resident training progress across successive years of orthopedic residency.

DEDICATION

To my parents, brother, and friends for believing in me and helping me achieve this major milestone of my life.

ACKNOWLEDGMENTS

I would like to extend my most sincere thanks to my mentor and guide, Dr. Krishnamurthy for being a constant source of motivation, support, and encouragement throughout my PhD. It is his pursuit for quality research and hunger for excellence that has honed my personality over the past five years at the Mixed-Initiative Design Lab. I am grateful to him for his unfettered trust in having me lead a newer research area and for his patience as I failed and learnt from my mistakes towards my growth as an academician.

I am also thankful to my committee members for their trust and support on newer research avenues. I appreciate their constant supporting towards my ideas and progress as I learnt through the past few years. I find myself to be one of those lucky few to work with humble and diverse intellectuals during my PhD. I extend my gratitude my collaborators at the McGovern Medical School at University of Texas Health Science Center for helping me broaden my research scope and thinking towards a multidisciplinary facet outside of traditional engineering applications.

I am indebted to my parents, brother and extended family who have supported my decision of pursuing a PhD and taught me to trust and believe in the process. I am thankful to the universe to have them by my side physically and emotionally during this entire journey.

I thank my friends and lab colleagues for being as much of a critique as much they have supported my journey. Their knack for clarity and often genuine curiosity has encouraged me to work harder towards producing quality research, moreover, presenting them in a manner that is accessible and easy to understand by everyone.

Finally, I am what I am, because of my study participants, for their volunteering and help in validate my research by providing key insights in different phases of my PhD dissertation.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supported by a dissertation committee consisting of Professors Vinayak R. Krishnamurthy (advisor) and Bruce L. Tai of the J.Mike Walker ’66 Department of Mechanical Engineering, Professor Shinjiro Sueda of the Department of Computer Science & Engineering and Professor Francis Quek of the Department of Visualization.

The physical setup design (Section 5.2.1), experiment and results (Sections 5.4 and 5.5) in Chapter 5 was performed in collaboration with Aman Nigam and Shantanu Vyas of the J.Mike Walker ‘66 Department of Mechanical Engineering.

All other work conducted for the dissertation was completed by the student independently.

Funding Sources

Graduate study was supported by J.Mike Walker ‘66 Department of Mechanical Engineering, Texas A&M University startup fund, AggieE_Challenge program, Texas A&M University Triads for Transformation (T3) program, National Science Foundation Cyber-Human Systems program (NSF-CHS Award #2008800), Orthopaedic Research and Education Foundation (OREF Award #0014566A) and Graduate Teaching Fellowship from the Texas A&M College of Engineering.

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1. INTRODUCTION

1.1 Motivation

"We must perceive in order to move, we must also move in order to perceive"
- J.J. Gibson, The Ecological Approach to Visual Perception (1966)

This aphorism is grounded in the psychological theory of *ecological psychology* [1], presenting a fundamental portrayal of the day-to-day activities in human lives. According to Gibson, our environment and events within it invoke"actionable properties" based on our perception of it; and conversely our actions have an effect on our environment, further changing our perception of it. This action-perception relationship cycle is an innate part of our daily lives and is constantly evolving and emerging, thereby, allowing us to perform gross as well as fine spatial actions that require motor control. As a case in point, skilled tasks such as sculpting or carving utilize different types of tools and brushes that "afford" or present the artist with a multitude of capabilities to create intricate and complex designs in a focused and careful manner. This innate ability to make coarse and precise motor actions finds its roots in the cognitive development theories focused on early childhood development. Piaget's well-known theories on cognitive development [2] highlight the importance of *fine-motor development* from childbirth, and its effect on improving cognition, hand-eye co-ordination, and dexterity as the child grows into adulthood. Therefore, our physical and perceptual learning experiences over several years helps us showcase this varied motor control, also, plays a key role in the the way humans adapt and interact with different environments and objects within it [3, 4, 5]. While these theories and observations hold true for actions performed in the physical world, existing AR/VR/MR interfaces fall short of affording the aforementioned sensorimotor skills in virtual environments. Specifically from the point of touch, hand-eye coordination and proprioception, that can leverage from years of physical and perceptual experiences of spatial manipulation actions in actuality. As a result, the lack of such action specific sensorimotor perception restricts the ability to perform precise and fine actions for manipulating spatial objects in the virtual world.

The **key challenge** motivating our work is the *need* and *ability* to transfer these perceptual

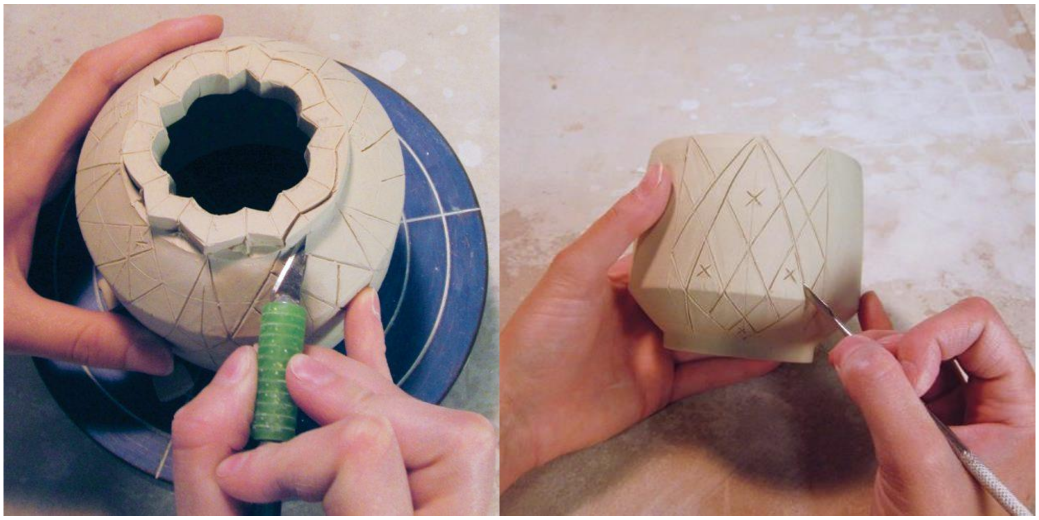


Figure 1.1: A clay artist carving intricate designs on a clay pot with a fine-tip precision tool

experiences from the physical to the virtual world in order to enable precise as well as gross spatial manipulation actions, as well as, leverage it to perform tasks that are not possible in the physical world. **Our primary objective in this work is to enable precise motor control for spatial manipulation actions in mixed-reality (MR) [6] systems.**

Motivating Scenario

Imagine a clay artist who is planning to start their own ceramic ware business for manufacturing hand-made and custom designed pots, plates, bowls, and cups. These custom designs are either created by the artist or requested by the customers. In order to get a cursory sense of how a design looks on a specific ceramic ware, the artist uses a software that overlays digitally created designs on surfaces and shapes of different geometries, which are the clay artefacts in this scenario. However, these digital overlays are unable to account for the physical constraints (geometry) as well as affording fine-motor perception and control necessary while chiseling and painting the ceramic objects using fine-tip tools and brushes respectively. The clay artist believes that they have the skill to create intricate designs on the ceramic ware, however, it may require multiple trials which will expensive from the point of time, money, and material. She hopes for a hybrid approach where she could simulate, practice and create the designs virtually with appropriate visual and haptic *feedback before committing to the actual physical task. Therefore, a virtual system that helps her leverage her physical and perceptual experience of sculpting towards virtual simulation of the same task.*

1.2 Goals & Objectives

As humans, we are constantly interacting with the physical world. Especially when we work with tools, our bodies and minds perform precise tasks all the time. Our virtual environments on the other hand, do not use our abilities simply because they have not been designed to do so. Therefore, our **broader goal** in this dissertation is ***to find ways that leverage our innate ability for performing precise actions in order to enable them in virtual environments and spatial tasks***. We define our research objectives from the point of enabling easy and intuitive transfer of physical skills and experiences to the virtual world for precise control, also, how can we study these fine motor actions and evaluate its efficacy. We discuss our objectives through the lens of proxemics, kinesthetics, and analytics in the subsequent sections,

Proxemics:

Goal: ***Investigate precise control for spatial manipulation actions performed close to the body***

Our key **objective** in this work is to explore how actions when performed close to the body affect precise motor control in MR interfaces. We begin by conducting an extensive literature survey and identifying some fundamental challenges in existing SUIs for affording precise manipulation actions, specifically, from the point of proximity to the fine motor control and hand-eye coordination. For this, we design a novel SUI called the Clock-Maker's Work-space (CMWS) allowing users to perform precise tasks close to their body, akin to the physical world. We evaluate this novel interface for simple yet fundamental precise spatial tasks often used in psychophysical studies, and compare it with an archetype MR interface — where actions happen at an arm's length. We also evaluate CMWS for its affordances to exercise precise motor control in comparison to precise tasks using physical objects. We draw key design guidelines from our investigation to guide the design of future AR/VR/MR interfaces that allow users to perform gross and fine motor actions in an intuitive and perceptually familiar manner. In proxemics, we conduct a broader study of precise motor control from the point of direct object manipulation action that involves complex coordinated motor movements across the shoulder, arm, wrist and finger movements These findings highlight that CMWS facilitates a rich spatial interaction workspace with the need for a deeper investigation of motor strategies and motor perceptions supporting different spatial manipulation actions and tasks.

Kinesthetics:

Goal: ***Investigate haptic-feedback for precise spatial rotation of virtual objects***

We narrow our investigation of fine motor control towards a single manipulation action, specifically, spatial rotation of virtual $3D$ objects. Our key **objective** here is to explore and investigate the role of haptics, specifically force-feedback in enabling precise, careful, and controlled manipulation of spatial objects. For this we design three haptics-supported rotation metaphors and conduct a systematic investigation of these algorithms for precise rotational manipulation tasks. For each algorithm, we evaluate user performance for spatial rotation algorithms with and without haptic support. We also identify a suitable algorithm from the propose set that supports easy and direct mapping of user's spatial actions, thereby, providing an intuitive spatial interaction experience. This work form a fundamental and critical basis on how haptics are crucial, critical and fundamental for precise control in SUIs. Despite designing algorithms that draw inspiration from actual perceptual experiences for object manipulation, the metrics to evaluate user performance for precise spatial tasks are under explored. This necessitates the need to study and analyze a real-world, fine motor task for forming a key understanding of the motor strategies involved in actual physical tasks as well as metrics to evaluate them, which can be further extended for virtual interfaces.

Analytics:

Goal: ***Measurement and analysis of physical tasks requiring precise motor control***

Taking a real-world precise task as our context, we study orthopedic bone-drilling with the underlying **objective** of investigating how precise actions are manifested in the physical world, as

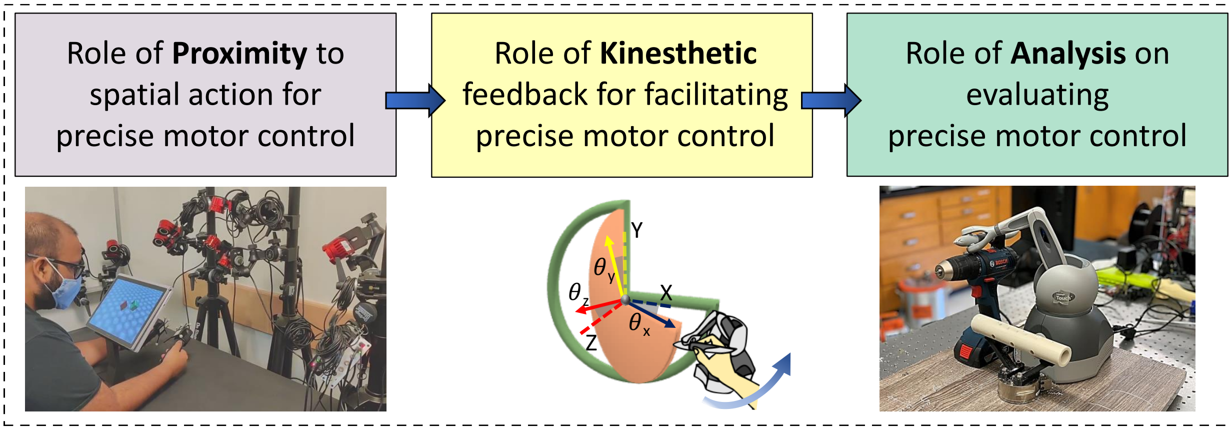


Figure 1.2: Sequential approach for investigating fine perception in spatial manipulation actions by studying the role of **Proxemics, Kinesthetics (Force-feedback)** and **Analytics** on enabling, measuring, and evaluating precise motor control.

well as, the right parameters to evaluate these tasks. We specifically focus on orthopedic surgery training for which we design a hybrid physical-digital setup to enable high precision bone-drilling training on a 3D printed bone surrogate, designed to emulate mechanical and perceptual properties of an actual bone. We design two variants emulating healthy and elderly adult bone properties. Our preliminary analysis show that raw data alone are insufficient to evaluate user performance as their representation are visually invariant for an expert and resident surgeon. This motivated us to develop a new performance metric with its theoretical basis in Laplacian noise characterization. Here, we compute a signature that captures the trajectory curvature, noise, and point distribution which helps differentiate between the drilling performance of a novice and an expert surgeon. In addition to evaluating training performance, the signature also helps analyze training progress across years of orthopedic residency.

1.3 Research Scope

Controlled spatial interactions encompass a broader research area within the scope of human-robot interaction, localisation of auditory information, as well as, interaction with smart technologies (IoT) [7, 8, 9, 10, 11, 12]. In such scenarios, users makes a conscious approach to interact with their virtual surroundings by performing premeditated actions with the virtual system, unlike fine motor actions which evolve as the user learns about their environment and the consequences of their actions on it. However, little is investigated with regards to this action-perception relationship that forms a fundamental building block for precise control in existing AR/VR/MR systems. The broader perspective of this dissertation is to explore on how we can enable, measure, and evaluate precise actions in spatial tasks (Figure. 1.2).

Proxemics: We systematically investigate precise control in spatial interactions by exploring the psycho-physiological concept of proxemics. The basis for this theory lies in the the well-known fact that precise motor control in physical actions is often exercised in close proximity to the operator performing them. We observe these in simple tasks such as tightening a screw into a hole, as well as, highly skilled tasks such as the clock-maker assembling mechanical components while repairing a watch. However, virtual systems are yet to draw from these real-world experiences and leverage this innate ability in order to perform gross and precise actions in spatial tasks. To overcome this fundamental challenge, we build on proxemics to conduct a systematic investigation as follows:

- Design SUIs that allow precise motor control for spatial manipulation tasks performed close to the body; and further draw guidelines for designing future spatial interfaces allowing fine-motor perception.
- Design meaningful experimental tasks that help measure, analyze, and study the enablement of precise control in spatial interactions, as well as, their performance compared to current state-of-the-art SUIs.
- Design and develop performance metrics for a deeper and fundamental insight on the fine-motor strategies (how a precise task was performed) followed for precise spatial control than existing metrics that simply evaluate the completion of a task.

Our fundamental investigation of proxemics scopes to identify a *perceptual motor sweet-spot* for performing precise spatial manipulation actions close to the body.

Kinesthetics: While we explored the role of proximity on precise actions, the scope is still broad for understanding the fine-perceptual cues such as visuo-motor coordination, touch, and proprioception that are crucial for fine motor control. Therefore, we further narrow our scope in understanding the role of haptics, specifically, force-feedback on precise control. In fact, haptics often complements visual feedback in performing physical tasks, and together they facilitate a synergistic visuo-motor coordination for performing these precise tasks. Moreover, humans are tool-making beings and since early mankind, tools have been use to perform a variety of task involving fine and gross motor control. On this thought, we focus on how haptic-feedback can be augment precise control in spatial object manipulation. While prior works have tried emulating the physical world as is, it is not the physical realism *per se*, but the perceptual familiarity in the haptic feedback that makes the overall interaction experience more intuitive. We systematically explore and investigate the role of haptics for precise motor control as follows:

- Design interaction metaphors that build upon physical haptics metaphors to enable fine and gross spatial rotational manipulation of virtual objects.
- Design haptic metaphors that complement the rotation algorithms so as to facilitate a perceptually familiar and intuitive spatial rotation experience for spatial object manipulation.
- Design experimental tasks to investigate and evaluate the role of haptic feedback in augmenting precise motor control for spatial manipulation
- Develop metrics to evaluate precise motor control with haptic support, such that the focus is on the task activity (path-based) itself than the end goals (state-based).

The overall intent to investigate and enable spatial actions is to allow for a tangible, perceptually familiar, and intuitive spatial interaction experience.

Analytics: In order to better understand precise control, it is fundamental to observe and draw from real world fine motor, task and leverage this knowledge towards the design and evaluation of precise tasks in virtual environments using appropriate metrics. Here, we conduct a systematic investigation of orthopedic bone surgery training with special focus on bone-drilling. This is a high precision task requiring well developed fine motor skills to perform safe and careful surgical operations with minimal danger to the patients. To help develop these skills, it is important not only to facilitate a means to practice these skills, but also, to develop metrics that evaluate training performance as well as provide insight on the fine motor strategies required for bone-drilling tasks. Therefore, with the goal of evaluating training performance and progress of resident surgeons for orthopedic surgeries, we investigate precise motor control as follows:

- Design a setup that facilitates the *physical* experience of as-real-as-possible bone-drilling experience, also, provides a *virtual* representation of the task performed for post-analysis of user performance.
- Design a data collection, processing, and analysis pipeline for an automated and detailed representation of user drilling performance parameters — position, force, and velocity.
- Develop user performance metrics for evaluating resident training performance with respect to an expert surgeon, as well as, monitor training progress across different years of orthopedic residency.

The idea is to transfer the respective observations, analyses, and skills to enable, measure, and evaluate precise spatial tasks for manipulating virtual objects.

1.4 Research Methodology and Approach

We follow a consistent methodology across all our works for investigating precise control in spatial object manipulation. We discuss these approaches as follows

1.4.1 Enablement

The most challenging aspect of this dissertation is the ability to help enable *precise control* in SUIs. Hence, it is critical that we design our interfaces to explore this possibility by allowing spatial actions to be performed close to the body (proxemics) for precise tasks. Subsequently, we also investigate the role of force-feedback (kinesthetics) in augmenting precise control by designing haptic-supported interactions for fine motor perception. Finally, we designed a setup to systematically investigate a high-precision physical task (analytics) to form a deeper understanding of how fine motor control is manifested in the physical world.

In proxemics, we design a novel SUI configuration that allows fine and gross motor actions to be performed close to the user body and overall, provides an intuitive interaction experience. Further, kinesthetics builds upon this notion of close space and, explores how haptics as a sensorimotor perception supports precise rotational manipulation of virtual objects. Whereas, analytics gives a fundamental and real-world insight on how we perceive, perform and improve upon our fine motor skills for precise physical tasks, and we do see with the example of orthopedic bone-drilling. We build a hybrid physical-digital setup, where the user drills through a 3D printed bone surrogate emulating physical and perceptual properties of an actual bone and we record the physical drilling data for further analysis.

1.4.2 Measurement

In order to validate the successful enabling of precise spatial actions, it is equally important to design appropriate tasks that allow for a systematic investigation of fine manipulation action in virtual environments. However, there are inherent challenges involved in identifying specific tasks due to minimal exploration in this area. Therefore, we design experimental tasks that draw from physical experiences as well as psycho-physical studies to measure user performance in precise spatial tasks. For proxemics, we build upon simple task of peg-and-hole to study visuo-motor coordination and fine-motor perception in precise spatial tasks. Further, in kinesthetics we design three haptic rotation metaphors complemented by perceptually coherent haptic algorithms that allow for fine as well as gross motor actions in rotating spatial objects. Finally, the orthopedic bone-drilling serves as a reference task to study, investigate, and analzye how precise control is manifested in the physical world.

1.4.3 Evaluation

One of the key challenges of investigating precise control in spatial interactions is evaluating the tasks. In fact, we have found through experiments that state-based metrics such as completion time and task error do not provide adequate insight on precise actions in virtual as well as physical tasks. We thereby focus more towards path-based metrics that help analyze simple peg-and-hole tasks from the point of how the fine actions evolve and emerge while docking the peg into the hole. On similar lines, we design an alignment-based task for studying precise spatial rotation with haptic support. Similar to the peg and hole task, we evaluate the rotation using path based metrics, but with more focus on rotational manipulation. Further, for analyzing orthopedic bone-drilling, the constrained nature of the task makes it difficult to distinguish between the expert and novice drilling performance. In fact, this motivated us to develop a new metric based on Laplacian noise characterization of user's drilling trajectory and compute a signature for it. Additionally, for qualitative analysis, we use metrics such as the NASA Task Load Index [13], open-ended feedback questionnaires, Likert scale rating [14], and think-aloud protocol [15]. We further conduct statistical analyses to identify differences and patterns across different interaction algorithms.

1.5 Research Questions

This PhD dissertation is motivated by the broader research question: *How do we transfer perceptual experiences for precise spatial manipulation from the physical to the virtual world ?* While working towards exploring solutions for the aforementioned question, we take three specific approaches of proxemics, kinesthetics, and analytics. Each approach puts forth specific research questions which we form our motivational basis as we proceed along the course of this research journey. We discuss them as follows:

Proxemics: Drawing from the knowledge that precise actions are performed close to the body, we answer the following research question,

Q. *What is the effect of proximity to action on precise motor control and how to embody it in spatial manipulation* ?

This further motivates us to narrow our investigation of precise control in spatial interactions.

Kinesthetics: Here, two specific research questions drive our systematic and fundamental exploration for investigating the role force-feedback in precise control for spatial manipulation of virtual objects.

Q1. *How can we utilize haptics to augment motor control in spatial interactions* ?

Q2. *What is the role of haptic-feedback on enabling precise motor control* ?

While investigating the aforementioned approaches, we realize that in order to transfer the perceptual and physical experiences from the real to the virtual world, it is imperative we study how precise actions are performed and evaluated in the physical world.

Analytics: Here, our investigation for a real-world precise task alludes to the research question asking,

Q. *How can we analyze motor control in a real-world precise task* ?

Overall, this dissertation is an intellectual and philosophical discourse built upon the theoretical basis of Gibson's theory on *ecological psychology*, with the broader goal of investigating how precise control can be afforded in spatial interactions.

1.6 Contribution

In this dissertation, we make three primary contributions towards exploring and investigating precise control in spatial interactions.

1.6.1 Interface Design Guidelines

We begin by conducting a set of controlled lab experiments to investigate how spatial interactions designed close to the body affect fine motor control and their influence on action-specific perception. We design and prototype a SUI called the Clock-Maker's Work-Space (CMWS) in the user's peripersonal space where we have the screen between the user (eyes) and their hands. Further, we draw a systematic comparison between a traditional MR systems allowing interactions at an arm's length. Through a simple and fundamental psychophysical task of peg-in-the-hole docking, we observed key differences in user performance and behavior favoring the CMWS. Also, our study demonstrated the value of action-specific perception as a guiding principle for designing systems and interactions for precise spatial manipulation. Further, we identify, characterize, and categorize key findings for *coarse* and *fine motor control* from the point of physical indexing, effect of shape geometry and size, and visuo-motor configuration. Not only do our findings align with the current psychology and motor behavior of spatial manipulation, but they also pave way for research in the design, development, and evaluation of future spatial interfaces, especially for 3D modeling and design applications.

1.6.2 Kinesthetic Algorithms

We further utilize these guidelines to design SUIs and investigate the role of haptic, specifically force-feedback in augmenting precise control for rotational manipulation. First, we contribute a set of three haptics-enabled interaction metaphors for precise rotation of 3D objects in virtual space. Following which 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.

1.6.3 Metrics for Precise Motor Control

One of the fundamental gaps in precise spatial control is the absence metrics that help evaluate the fine spatial actions. Instead existing metrics are more focused on analyzing completion time and task error as means to evaluate motor control in spatial tasks. From the perspective of proxemics, we evaluated CMWS using path-based metrics typically used for surgical tasks [16]. However, these metrics are focused on the shortest path to perform peg-in-the-hole type of tasks, without providing insight into the motor strategies at the wrist and finger level dexterity as exercised by users for fine motor manipulation actions. With this motivation, we further design a metric that captures the noise, curvature, and distribution of points for precise physical tasks such as orthopedic bone-drilling. This metric computes a signature that is used to evaluate training progress for resident surgeons, as well as, training progress during successive years of orthopedic residency.

2. CURRENT STATE-OF-THE-ART & KNOWLEDGE GAPS*

In this chapter, we discuss the current-state-of-the-art and existing knowledge gaps through an extensive literature review encompassing the research areas explored, studied, and investigated by our work. The following works not on help us identify key knowledge gaps, also, inspire the different chapters of this dissertation.

2.1 Action & Perception

The perception of peripersonal space is tightly linked to Gibson's position of ecological psychology [17], which gave rise to the notion of perceived affordance, a concept we use abundantly in the design of physical experiences. From the perspective of neuropsychology, peripersonal and extrapersonal spaces are defined by our brains with our body as the reference — peripersonal space is *"centered on body parts (i.e., hand-centered, head-centered, and trunk-centered)"* and *"is for the interaction with objects and people in the space around us"* [18, 19, 20, 21]. In fact, peripersonal space is not a "*single, distance-based, in-or-out zone*" [22]. To this effect, Bufacchi et al. also show evidence that indicates a more fuzzy, action-dependent, context-dependent nature of peripersonal space that can have multiple components (say a union of volumes around the head, torso, and hands) and also changes due to factors other than proximity [22]. A more recent finding by Hecht et al. describes the peripersonal space within a horizontal circular space of 1 meter radius centered at the torso [23]. Longo et al. and Witt et al. provided early evidence to this fact and noted that the perception of what comprises "near space" is flexible and changes with usage of tools. Specifically, tools increase the mental range of near space (at least within the range of around 1.2 m) [24, 25, 26]. As a result, the fundamental behavior in object manipulation can change drastically based on the space where objects are located [27]. Davolii noted: "*By shifting an*

*A portion of this chapter is adapted with permission from Mohanty, R. R., and Krishnamurthy, V. R. "Kinesthetic Metaphors for Precise Spatial Manipulation: A Study of Object Rotation." ASME. J. Comput. Inf. Sci. Eng. April 2021; 21(2): 021010.

object from extrapersonal space to peripersonal space, the object may appear closer while remaining in the same physical location, an effect that would have implications for how one chooses to perform visually controlled tasks" [28]. Similarly, Galigani et al. discuss the effect of tool-use in an active-usage and observational scenarios where the sensory perception from the active-tool usage helps get a better sense of the peripersonal space than simply observing an action being performed from a third-person perspective [29]. This is a critical observation that needs to be emphatically incorporated in the design of spatial manipulations.

2.2 Proxemics in Spatial User Interfaces

Looking across the Mixed Reality continuum [30, 31, 6], we find that interfaces with head mounted displays (HMDs), Desktop-VR, Tablet-AR, and Augmented Virtuality Displays work within medium to large interaction volume for 3D object manipulation tasks [32, 33, 34, 35]. While there are several works that study SUIs in the peripersonal space, they primarily focus on social behavior of virtual avatar of humans in a VR environment towards enhancing user engagement and immersion [36, 37, 38, 39] or *social-interaction through cross-device interaction* [40]. Another popular area is *ubiquitous computing*, where the focus is on developing spatially-aware systems such as smart display setups [41, 42, 43, 44, 45, 46, 47, 48], and input-control mechanisms that control hardware and their software elements using the portable hand-held devices that can be controlled in *close proximity* to their body comfortably [49, 50, 51].

The aforementioned application scenarios focus more towards an adaptive visual feedback based on the *user's proximity to a spatially-aware display* [43, 45]. In other words, the context for a given action is already pre-determined in terms of the location of the display that is often a large device (from the perspective of peripersonal space) and is also far away from the user. As a result, the user ends up making a conscious effort to first reach the environment (both physically and mentally) as a *pre-motor strategy* to manipulation such that these displays or smart devices are in close proximity to the user. Little is currently known about 3D design and shape manipulation-type interactions in close-to-the-body scenarios where precise and fine motor actions are actually carried out.

Recent works in HCI and Psychophysics by a few, such as Jetter et al. [52] showcase a *spatially-aware* interactive VR space that allows for $3D$ sketching as well as post-WIMP interactions towards a computer-supported design tool [53]. Fossataro et al. [54] study the role of visuo-motor incongruence in VR highlighting the need for a co-locate visual and perception space. Lee et al. [55] discuss how a third person perspective of a digital avatar's peripersonal space affects the user's navigation strategies in a virtual environment. Seminal works such *HoloDesk* [56], *SpaceTop* [57], and *MixFab* [58], that capture peripersonal interactions are by and large application-oriented. While there are in-depth studies on understanding $3D$ sketching actions in VR applications [59] and docking [60], they are still representative of the large-screen *distant* interaction approach to spatial manipulation.

If anything, these few recent studies show that the role of proxemics for spatial interactions is quite rich and still largely remains under-explored. There are several key unanswered questions such as: *how different are uni-manual and bi-manual tasks in precise tasks?, and where should the hands, eyes, and the screen be situated for best performance in precise manipulations?*, etc. Our work seeks to systematically explore these questions by building on the current and growing understanding of proxemics for spatial interactions performed in the peripersonal space.

2.3 Proprioceptive Feedback

Proprioceptive and kinesthetic control are inherent to humans in any physical interaction and thus, play a key role in design processes as well as computer-supported design tools that involve human action and perception [61].The lack of force (kinesthetic control) or tactile (touch) feedback as observed commonly across these systems, severely impedes the ability to make fine spatial control; as a result, object manipulation becomes a difficult and *high effort task* [62]. This is mainly experienced with spatial actions performed close to the body such as MR systems for mid-air pointing and selection actions [63, 64]. Proprioception at an egocentric distance around the periphery of human body helps reduce dependency on the visual feedback for manipulation actions in local and distant mid-air interaction spaces. Recent work by Plaumann et al. discusses a formal study focused on studying the visuo-motor relationship in spatial actions [65]. While the study primarily focuses on *macro*(coarse), as well as, *micro*(fine-grain) interactions, the key finding her is that the users experience a *visuo-motor mismatch* for spatial pointing tasks at distances away from the body, and this discrepancy reduces in pointing actions performed close to the body. Similar results as discussed by Popvici et al. is showcased through *displayless* IoT device interfaces whose virtual controls and shortcuts are spatially placed in user's personal, peripersonal, and extrapersonal spaces [66]. Their observation states users performing *large* interactions with objects in the extrapersonal space and actions of *smaller amplitude* for the ones in closer vicinity of the body. On the other hand, Argelaguet et al. note visual dependency in virtual environments attributing to distinct motor and visual spaces for spatial interactions [34]. Further, DeBoeck et al. [67] also demonstrate that interactions performed proximal to the body improves kinesthetic control by exploiting proprioception. The key finding relevant for our work is that while proprioception enhances manipulative precision close to the body, the same is not true for for distal interactions, and these can be further influenced by other sensory perceptions such as visual, audio, tactile, and kinesthetics [68].

Again, there are some questions that we seek to answer such as: *what are the motor strategies that take effect in peripersopnal space, and how should these strategies be supported through new interactive devices?, etc.*

2.4 Bi-manual Action in Spatial Interactions

Works by Hinckley et al. [69] studied cooperative bi-manual interactions for virtual manipulation and provides a strong evidence for augmenting hand-eye coordination through the use of two hands in conjunction with haptics feedback. In general, two-handed interactions in coordinated tasks have been shown to increase cognitive engagement of the user [70, 71, 72] and efficiency of 3D object assembly [73]. Several works explore the advantages of bi-manual spatial interactions [74, 75, 76, 77, 78, 79, 80, 81] for object selection [82] and manipulation (rotation, translation, scaling) of 3D objects. Alternatively, few recent works [83, 84] showcase a *hybrid 2D-3D* input mode using a tablet surface and a 6DoF controller for bi-manual interactions in an VR setup. Similarly, Brandl et al. [85] explore the combination of two-handed interactions with pen and multi-touch inputs on a surface. Regardless of the wealth of literature, we believe that much is to be discovered regarding bi-manual interactions, when seen in the context of proprioception in peripersonal spaces.

2.5 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 [86]. 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. [87] 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 [88]. 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 [89, 90, 91], 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. [92] 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. [93] 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. [94, 95], 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. [96] designed an evaluation metric to measure the DoF used for different spatial manipulation interactions. Further, drawing from the work by Jacob et al. [97], 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. [98] 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 [87] for a large variety of applications. In their works *IloveSketch* [99] and *EverybodyLovesSketch* [100], 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 [101, 102, 103, 104, 105, 106].

2.6 Spatial Manipulation

In response to the 2D user input, mid-air (spatial) interactions provide a direct way of interacting in 3D space [32, 87, 88] 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 [107, 108, 109, 110]. Alternatively, Fu et al., describe NUIs as hardware or software interfaces that leverage the *human capabilities* for spatial manipulation [111]. 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. [112] 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. [113] 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. [114] 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. [115] 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 [57, 116], 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. [117] 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

2.7 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 [97]. 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 [118, 119]. 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* [120, 121, 122], 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 [123, 124]. Further, novel kinesthetic metaphors have been developed for *mid-air haptic displays* in order to improve virtual design tasks using 6 DoF haptic devices [125, 126, 127, 128, 129, 130, 131]. 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 [132]. 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 [131, 133]. 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. [134, 135] 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 [98, 136]. As stated by Klemmer et al. [137] 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 [61, 110, 138, 139, 140, 141, 142, 143].

2.8 Orthopedic Surgery Training

Orthopedic surgeries are a set of high-precision tasks that necessitate the ability to make fine and careful motor movements while performing a surgical operation. The goal is to minimize any risk of damaging the bone, nerves, or tissues [144] during the surgery, thereby, ensuring patient safety. As a case in point, orthopedic surgery training and evaluation is critical, as well as, crucial for helping resident doctors build on their hand-eye coordination skills, and fine-motor perception skills. In this paper, our focus it to facilitate evaluative means for monitoring orthopedic resident training progress over the duration of their residency program. From our interviews with expert surgeons, we learn that the evaluation of orthopedic resident training performance is not merely qualitative but completely *subjective*. The expert surgeon observes the residents visually and grades their performance based on that observation.

Prior works have proposed techniques to improve orthopedic resident training from two primary perspectives — improving patient safety and reducing the training time required to achieve proficiency in bone drilling and screw placement tasks. Recent studies have showcased improvement in bone-machining skills through surgical simulations in arthroscopy, dentistry, craniomaxillofacial and orthopedic surgery tasks. The majority of these studies are focused on bone drilling [145, 146]. Previously, systems have employed training on cadaveric and animal bone specimens with some levels of success. Review literature [147, 148] highlights the presence of a short term skill acquisition using cadavers for orthopedic surgery training.

Cadaveric training and animal model are the traditional orthopedic simulators used for surgical training. They serve as the best alternative to live surgery [149] as they offer realism, tactile feedback, and awareness about the anatomical construction [150]. However, human cadavers are expensive, and their limited availability restricts their widespread use. Further, cadavers require regular maintenance in special facilities and are also susceptible to disease transmission. To address the shortcomings of cadaveric training, VR-based orthopedic simulations have been widely researched. They are employed for skill acquisition, decision-making, pre-operative planning [151], and real surgery [152]. These simulators eliminate the requirement of cadavers or animal bones and reduce operative time to improve the performance of surgical trainees [153]. However, VR simulators are expensive and do not provide a realistic environment nor physical, tactile feedback.

2.9 Evaluating Bone-Drilling Performance

Evaluating bone-drilling performance is one the most challenging aspects of orthopedic surgery training [154]. Although teaching surgical techniques is a significant residency task, traditional approaches for surgery training assessments are inconsistent and subjective [155]. As a result, it is difficult to explicitly identify differentiating factors between the experts and resident surgeons, also, the drilling behavior that the resident could improve upon. Different types of surgical simulators offer different kinds of drilling environment. Hence the performance assessment technique also varies. One common factor in assessment is the onset of osteonecrosis, a disease resulting from thermal damage to the bone tissue. [156]; which is difficult to simulate outside the OR in an artificial training setup.

The temperature generated during the bone drilling depends upon various parameters such as drill geometry, rotational speed of the drill bit, drilling forces, and rate of cooling. Most investigations based on temperature are related to rotational speed and drilling forces. There is a general agreement in existing literature that bone temperature increases with the drill speed [157]. A more recent work [158] has been able to further narrow the effect of temperature near the drill entry-exit point with regards to bone-material, drill bit geometry, and drilling stance. The drill feed rate is another parameter in determining the heat generated during bone drilling. Generally, at higher feed rates, the drilling time decreases, and less heat is accumulated. However, high feed rates might also imply higher forces and higher heat generation [159]. We observe that, recent works are still in process of identifying objective parameters to evaluate drilling performance, before standardizing a proper quantitative methodology.

One of the key parameters in gauging drilling performance is the plunging distance. Plunging distance is the distance that a drill bit might travel after drilling through the second cortical region. Bone drilling requires precision in hand motion, and a greater plunging distance may cause soft tissue damage. Kazum et al. [160] built a low-cost drilling simulator to train orthopedic residents in reducing the drill plunging depth and found that the plunging depths of the junior residents were significantly greater than orthopedic specialists (7.00 mm vs. 5.28 mm). However, no significant difference was observed between the senior residents and the orthopedic experts (6.33 mm vs. 5.28 mm).

Different researchers have suggested various approaches to judge drilling performance based on individual parameters. However, not much work has been reported in developing a single parameter to compare the drilling performance of a novice (first year resident) to that of a specialist. As seen, all the performance parameters are related to motion (feed rate, time in the bone, plunging distance).

2.10 Overall Knowledge Gaps

In this section, we expand and discuss upon the knowledge gaps in each of the previous sections and how do they connect with precise motor control in spatial interactions.

Proxemics in Spatial User Interfaces: Precise control in physical actions are manifested close to the body, however, the effect of proximity to action is little investigated for spatial interactions. In fact, existing interfaces by and large are representative of the large-screen *distant* interaction approach to spatial manipulation. Thereby making it difficult to perform precise spatial tasks in an intuitive and perceptually familiar manner.

Proprioceptive Feedback: Proprioceptive perception, specifically the awareness of ones arms being close to body, affords the capability to exercise fine-motor control. However, the same is not true for arm's length interactions as found in conventional mixed-reality interfaces. The knowledge gap is how interfaces could afford proprioception and manifest motor strategies for performing precise spatial manipulation tasks.

Bi-Manual Action in Spatial Interaction: Research shows that bi-manual interactions are crucial in augmenting hand-eye coordination and proprioceptive cues for efficient spatial manipulation performance. Despite this knowledge, bi-manual interactions are utilized for large scale shape manipulation tasks as well as multi-modal interfaces, complemented with pen or multi-touch inputs. In fact, bi-manual perception provides a rich interaction space that needs to deeply investigated for precise motor control.

Spatial Manipulation: Spatial manipulation *per se* has been investigated extensively and despite decades worth of work, pen and mice inputs are still a popular choice. While intuitive, spatial manipulation actions suffer from fatigue due to prolonged suspension, lack of sensory perception, and a learning curve due to technological constraints. Therefore, the knowledge gap is in identifying how we can integrate sensory perception and motor skills towards *controlled* spatial manipulation of virtual objects, also, mitigate fatigue for prolonged interaction sessions.

Kinesthetic Support for Mid-Air Manipulation: Prior works have discussed kinesthetic feedback mainly from the point of curve modeling and 3D sketching interactions, however, use of force-feedback for spatial manipulation is little explored. Case in point, these explorations are limited to translation and scaling based tasks. Investigating rotational manipulation needs a systematic and fundamental exploration of haptic support for an intuitive and perceptually coherent spatial object manipulation experience.

Orthopedic Surgery Training: The key knowledge gap in existing orthopedic surgery training is the severe lack of setup configuration that allows for as-real-as-possible bone-drilling interaction experience. Existing training approaches include commercially available bone surrogates, but the trade off is in perceptual feedback to an actual bone in lieu of bone-like mechanical properties. Similarly, cadaverous specimens are a good training apparatus, however, these samples are not consistent and demand special storage requirements, thus, making them an expensive option.

Evaluating Bone-Drilling Performance: On interviewing expert surgeons we found that existing methodology for evaluating resident training performance is not only qualitative, it is subjective as well. This implies that the training is dependent on the expertise as well as the individual evaluating the resident surgeon. There is need for well-defined objective, and preferably quantitative metric over the existing subjective and qualitative way of evaluating the training performance of resident surgeons.

In the following chapters, we discuss the technical contributions in detail for all three approaches towards investigating precise control in spatial interactions.

3. TOWARDS CLOCK-MAKER'S WORK-SPACE: EXPLORING SPATIAL INTERACTIONS CLOSE TO THE BODY

3.1 Overview

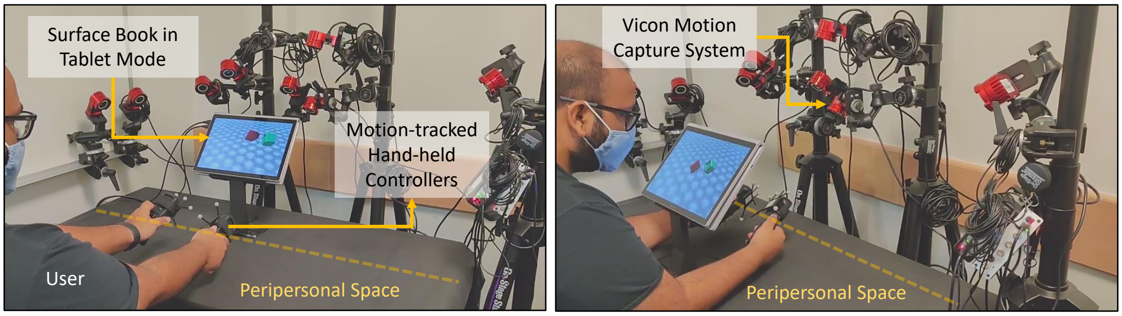
Advances in Mixed Reality (MR) systems have gained significant interest in their utilization as computer-supported design tools [161]. Their commodification has helped create a large body of work on spatial interactions, tangible user interfaces, and immersive displays [162, 163, 6]. At least in principle, the developments in MR systems and interaction techniques [32, 34, 35] are generally aligned with the embodied interactions viewpoint wherein the intention is to incorporate bodily practice into interactions with virtual artifacts such that users *perceive the artifact as an extension of themselves; they act through it rather than on it* [137, 164]. History, limitations of technology, and inertia of development have combined to favor interaction in the extrapersonal space (space farther away from the body) in HCI [19]. For example, the distal display monitor and the ubiquity of mouse-based interaction have pushed computer-aided design (CAD) to arms-length interaction [165, 80, 166]. Early limitations of stereoscopic displays and the interest in immersive experience created a bias toward deploying display resources to the visual periphery at the expense of the visual fovea [167, 168] with which fine motor ability is paired.

3.2 Motivation

Recent studies in HCI literature [169, 170, 171] discuss a decrease in visual perception of a virtual object when placed in the extrapersonal space, as well as, its influence on the manipulation action. We argue that the design methodologies for spatial interaction techniques need to reconcile with our mental representations of the actions we perform in physical spaces with physical objects — *the proximity of the action, the size and shape of the manipulated object, and the corresponding visual feedback* should be in synergy. The inspiration for our work comes from some seminal systems such as *HoloDesk* [56], *SpaceTop* [57], and *Mix-Fab* [58] that underscore the importance of spatial interactions in close to the body. However, these and several related works are primarily focused on specific application contexts such as digital and physical prototyping. There is currently no in-depth analysis of precise bi-manual manipulation of virtual objects in the user's peripersonal space. We argue that that spatial interactions for 3D design in the digital world must closely mirror those that we, as humans, perform in daily physical tasks close to our bodies. Our goal in this paper is to explore the interaction space that merges physical actions with virtual interactions in a way that it supports our internal mental representation of the physical world.

3.3 Basis & Inspiration

Gibson's seminal adage that "*perception is for action*" informs our research [17]. The corollary of this concept for interaction design is that action should be designed to match the powers of human perception. While under-explored, past HCI literature discuss similar thoughts on co-located action-perception space from the perspective of proxemics [19], specifically in the context of ubiquitous computing [172, 41]. Taking inspiration from from *Blended Interaction* [52] and *Situated Space Model* (SSM) [173] we seek to re-imagine spatial interactions with digital objects in the perceptual sweet-spot. We call this sweet-spot, the *Clockmaker's Workspace* (CMWS) to pay tribute to the extreme dexterity with which humans as tool-makers and tool-users [174] are able to focus within this space. Indeed, even the late development of writing skills in our evolutionary timeline engages this near space in front of the human torso, also known as the *peripersonal space* [175], as we crouch over our table-tops to author, draw, and engrave. We argue that this space has been granted surprisingly little research attention in the various configurations of HCI, which focus computational resources at arms-length interaction, or to distant walls which we have little natural capacity to affect. On the contrary, following Norman's point of view [176], spatial interfaces that truly support 3D design will be *invisible* in that they will only require users to act in the same



(a) Eyes→Hands→Screen (EHS) (b) Eyes→Screen→Hands (ESH)

Figure 3.1: We investigate spatial interactions close to the body with two experimental setups (visuo-motor configurations) designed for spatial interactions in the user's peripersonal space. Each setup has MS Surface Book converted to a tablet and high-precision motion tracking with Vicon motion capture cameras. (a) In this study configuration the users interact before the display setup (eyes→ hands→ screen), and (b) in this configuration users interact after the display setup (eyes→ screen→ hands).

way that they act in their day-to-day interactions with their physical environment. Our goal in this paper is to address some fundamental research gaps in current HCI practices towards the realization of the Clockmaker's Workspace; which we investigate using an MR system in order to highlight the role of peripersonal space for precise spatial interactions.

3.4 Designing the Clock-Maker's Work Space

In the following sections, we discuss and elaborate on the rationale and methodology for designing small interaction spaces for 3D object manipulation in AR/VR systems while preserving the user's physical peripersonal space. There are three primary factors that guided the design and implementation of our peripersonal spatial manipulation system, the clock-maker's work-space.

In order to realize our long-term vision of CMWS, it is important to identify, understand, and tackle some key issues in existing research methodology for MR to perform precise spatial interactions. In response to this, we design and prototype two spatial user interfaces from the perspective of exploring precise object manipulation actions in the peripersonal space.

3.4.1 Factors affecting Interaction Design

Below, we discuss some fundamental factors that influenced our design decisions for implementing the hardware setup, user tasks, and the experimental design for the exploration of CMWS:

- **Anatomy:** Peripersonal space varies with the user's body structure, further classified based on the body-part in action - *hands, face,* and *trunk* [177, 18, 19]. In fact, Galigani et al. [29] make a note that active tool-usage in the peripersonal enhances the user's proxemic perception, thus, aiding improved spatial manipulation. In our work, we focus on the peripersonal space defined by the upper limbs, mainly to observe and analyze comfortable interaction distance for precision tasks in MR systems and its relation to the anatomical peripersonal space, specifically the hand, i.e. the *perihand space*.
- **Interaction Space:** There are two factors of the workspace that demand attention. The first is the **location of the interaction space** with respect to the body (specifically the torso). This volume should represent what is currently known as the peripersonal space in literature. The second factor is the **volume of the interaction space** which is defined by the physical limits in sagittal, transversal, and coronal directions [178] from the human body. The manipulation is meant to occur within this volume. We utilize *action field theory* as proposed by Bufacchi and Ianetti [22] to determine the extent of motor control based on object proximity. This theory is of essence from the perspective of interaction amplitude i.e. *coarse* and fine motor strategies adopted by the user in order to manipulate an object in 3D space based on their distance from the object [66]. In fact, this could also be representative of the user's spatial trajectory patterns in tasks where an object is moved to an arbitrary target in 3D space [60].
- **Robust Tracking:** In our exploration, we assume that the manipulation is assumed to be performed with a hand-held object which may either be a controller such as a

Wii remote or some 3D printed shape whose position and orientation is being tracked in space. The key challenge here is that the tracking must allow for precise actions. Precise actions in the peripersonal space often require "*modulation of closeness, digit, arch, and thumb opposition synergies, with different control patterns per grasp*" [179]. While, Reissner et al. have attempted to standardize motion capture at the hand level, there are pertaining issues such as *skin stretch*, *joint movement*, and *occlusion* which makes it difficult to explore precise actions at the fingers and thumb level, thus, our work investigates motor precision at the wrist level (which forms the based of the hand) [180].

– **Visuo-Motor Configuration:** This is one of the most important factors that influences our exploration. The average proximity of a user to the manipulated object is somewhere between (1.5 ft to 4 ft), which falls between the proxemic ranges of *intimate to peripersonal space*. It can be generalized as a space bounded by a user's *arm length* [181, 19]. Current MR interaction design methodology integrates actions that are either performed at the boundary of one's peripersonal space (arm's length) or the visuo-motor space is disconnected, which contradicts the need for a co-located action-perception space for precise spatial actions.

3.4.2 System Design & Development

Taking the visuo-motor co-location as our fundamental building block, we designed and prototyped two interfaces (Fig. 3.1) where the interaction volume falls within the peripersonal space of any user. We designed this space in tandem with the motion capture camera system so as to achieve a small interaction volume while maintaining tracking robustness. The common hardware for both of our experimental setupscomprised of a Microsoft Surface Book laptop computer with an Intel Core i7-6600U CPU (3.4GHz), 16GB of GDDR5 RAM, and an NVIDIA GeForce GTX 965M graphics card having 2 GB video memory, running 64-bit Windows 10 Professional Operating System. The laptop was converted to a tablet so as to present an early prototype of CMWS while maintaing the GPU and processor speed for the MR application.

3.4.2.1 Visuo-motor Configurations

Our first experimental setup (Fig. 3.1(a)) is representative of traditional MR systems where the user performs spatial interactions in front of the display screen in this paper we refer to this visuo-motor configuration as *Eyes→ Hands→ Screen* (EHS) based on the sequential arrangement of the user, their hands, and the display. Our second experimental setup (Fig. 3.1 (b)) is MR system renditioned for Augmented Virtuality (AV) satisfying 4 out of 6 notions for MR namely *continuum, collaboration, combination*, and *alignment* [6]. Similar to EHS, we refer to this this visuo-motor configuration as *Eyes→ Screen→ Hands* (ESH) and was designed with the intention of: (a) co-locating the virtual and physical (motor) peripersonal space for high-precision tasks, and (b) reducing occlusion caused by placing the user's hands in front of the screen [168, 182, 183].

3.4.2.2 Interaction Space:

Based on the prescription made by Bufacchi and Ianetti, our interaction space is located within the range of $45 - 60$ centimeters ($1.5 - 2$ feet) from the torso (the range signifies anthropometric variations across different users). As for the volume (i.e. the physical,limits), we follow an iterative approach starting from a standard table-top dimensions. The main challenge here is to determine a reasonably small working volume, suitable for precise manipulations while maintaining robust tracking.

3.4.2.3 Tracking Methodology:

Our user evaluation application was developed using Unity alongside the Optitrack Motive API for streaming raw motion data from the cameras. Nintendo Wii remotes tracked by reflective markers were used as the input devices for spatial manipulation tasks in both setup configurations. We used eight Optitrack Flex 13 Motion Capture cameras (field of view:

56°, refresh rate: 120 Hz) to capture an interaction volume measuring 2 ft x 2 ft x 1.5 ft. A mean error of 0.035 mm was recorded in tracking very small objects (1.5 cm to 2.1 cm in diameter or edge length). To note, the camera configuration was an iterative process to ensure excellent tracking coverage and minimizing any blind-spots due to the compact nature of the interaction space. We used specialized calibration wands and squares commercially designed for small to medium capture volumes having a standard deviation (σ) of 0.002 mm in calibration accuracy. Our reason for not going ahead with a single-camera motion tracking devices [184, 185, 186] is the limited interaction volume measuring 0.5 ft x 0.5 ft x 0.2 ft for tracking hand movements [187] and lack tracking robustness with a relatively higher σ of 1.2 mm [188] in calibration accuracy. Given our need for precise and robust tracking, we choose 6 DoF motion capture camera system for robust, sensitive, and accurate mapping of user movements.

Based on our interaction design methodology in the peripersonal space, we conducted a set of controlled lab experiments to test the effect of each experimental setups on user performance for bi-manual tasks.

3.5 Experiment Design

Our experiment design was based on a systematic and iterative approach to investigate precise spatial manipulation in the peripersonal space. We conduct 2 controlled lab experiments using EHS and ESH setup configurations with human-subject participation. Based on the nature of the experiment, these experiments are either between or within subjects in nature. In the following sections we describe the participation pool, study tasks, experimental controls, and evaluation metrics followed across all experiments for various comparisons.

3.5.1 Participants

We recruited a mix of 33 (16 female, 17 male) graduate and undergraduate students ($18-30$ years old) from engineering, architecture, and visualization majors. Around 15 participants

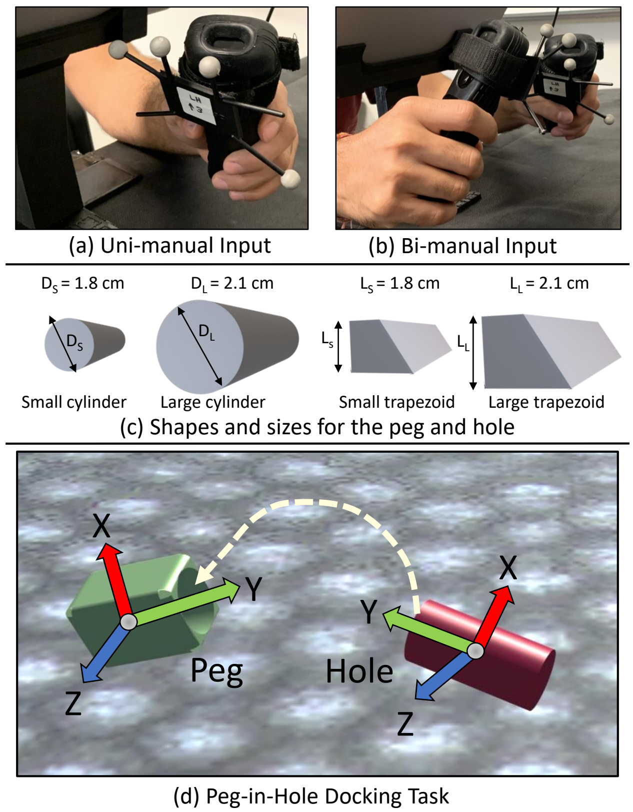


Figure 3.2: (a),(b) Motion-tracked Hand-held controllers held with power grasp to allow fine wrist motor control and compensate for any error in spatial manipulation action; (c) Cylinders and Trapezoids for peg-in-hole docking task with presence and absence of rotational symmetry respectively; (d) A screenshot of the peg-in-hole docking task from the actual study interface.

had prior experience with VR/AR systems, and 9 of them had experienced mid-air gesture and interactions through gaming consoles, mixed-reality headsets, and prior user studies. Each participant was ensured to be healthy such that they could comfortably use both of their upper limbs.

3.5.2 Selecting a user task to study precise manipulation

Past research on peripersonal space shows commonly used tasks such as visual matching of shapes placed at different distances away from the participant. The intention here is to test the participants based on their distance estimation of the virtual objects and the error in matching them with their respective targets. However, such tasks lack the level of control and fine motor movement demanded by precise manipulation. For our experiments, we chose a 6DoF peg-in-hole docking task (Fig. 3.2 (d)), which is moderately complex and fundamental towards understanding precise spatial actions in the peripersonal space. The task required for the participants to use 6DoF control in order to position, align, and dock the peg into the hole. In fact, psychophysical studies have widely used this approach for understanding the role of haptics and visual guidance in spatial interactions [189, 190]. Also, for human-assembly tasks [191, 192]. Past HCI literature has shown studies using docking-based shape assembly tasks for evaluating spatial user performance in terms of precision and accuracy [193, 194, 69]. We developed a user interface on Unity3D that shows a pair of peg-and-hole shapes on the display screen across both visuo-motor configurations (Fig. 3.1). Each peg-and-hole pair has two shape variants — cylinder and traepzoidal prism (for brevity, we use the term "trapezoid") (Fig. 3.2 (c)) based on the presence and absence of rotational symmetries respectively, thus, posing a challenge for the participants in aligning the peg with the hole. We also hypothesized that the cylinder has a relatively smooth surface and edge geometry compared to the trapezoid, and was hypothesized to be docked with more ease, whereas, the trapezoid with relatively sharper edge geometry would be relatively difficult to dock. Further, each shape has two size variants — large and small, thus, exploring the scalabality of the interaction design space based on varying shape types and sizes. Past literature shows evidence that change in object sizes affects visual, proprioceptive, and kinesthetic sensory perceptions [195, 196, 197].

3.5.3 Procedure

Each study took approximately 30 minutes and each trial took 15 to 30 seconds to complete. In total, 1056 trials were recorded across the two visuo-motor configuration spaces. Each session started with the general introduction of the motion capture system and the study interface, familiarizing the users with the motion-tracked hand-held controllers to be used as an input to manipulate the peg-and-hole shapes before or after the screen based on the visuo-motor configuration. The hand-held controllers (Figure. 3.2 (a), (b)) were strategically placed with reflective markers on them to enable robust tracking. These controllers were generic Nintendo Wii controllers allowing the participants to form a *precision grasp* around them and be able to make precise motor movements about the wrist [198, 199, 180]. These controllers have been designed keeping spatial interactions in the mind, and, therefore, stand as a suitable fit for our study tasks.

3.5.3.1 Preparation & Control

In order to maintain robust tracking throughout all user trials, we calibrated the motion capture system after 5 participants, in addition to calibration at the beginning of each study calendar day. We also asked the participants to remove ornaments and accessories such as jewellery, watches,.etc worn on their hands and wrists that have reflective surfaces which can give false tracking data. Further during the study, we monitored each participant's spatial motion to avoid actions performed outside the range of our interaction space which created tracking blind-spots. In the beginning of the study, we also allowed the participants to adjust their posture with respect to a given setup configuration for robust and accurate motion tracking. Finally, they were asked to fill an initial demographic questionnaire before beginning with actual study tasks.

3.5.3.2 Study Tasks

The experiment subsequently consisted of the following tasks:

Practice: Participants began by getting familiar with the motion capture system by manipulating a set of sample 3D shapes using the physical shapes or controller inputs depending on the control group for the initial 5 minutes of the study. We ensured that participants adhered to the *study protocol* (Section. 3.5.3.1) and acquired adequate practice before starting with the trials.

Uni-Manual Manipulation: In this case, either hand controlled the peg in the virtual space using the motion-tracked hand-held controller (Figure. 3.2 (a)), whereas, the hole was at a fixed orientation of $45°$ in the virtual 3D space. The orientation for the hole was computed based on preliminary trials so as to maintain an optimal elevation that keeps the user's physical actions in the small interaction volume while ensuring robust tracking of the peg input control. The trials were randomized using Latin Square and a new peg-hole shape and size pair was evaluated for each successive trial. For uni-manual manipulation, each participant per control group performed 6 trials per shape per size (24 trials per participant) and a total of 528 trials were recorded for all 22 participants for both study configurations.

Bi-Manual Manipulation: In the bi-manual approach, each hand was responsible to control either the peg or the hole based on user-handedness. The user actions were constantly monitored by the study coordinator so as to avoid movements outside the tracking volume. Here also we randomized the trials using Latin Square and a new peg-hole shape and size pair was evaluated for each successive trial. For bi-manual manipulation as well, each participant per control group performed 6 trials per shape per size (24 trials per participant) and a total of 528 trials were recorded for all 22 participants for both study configurations.

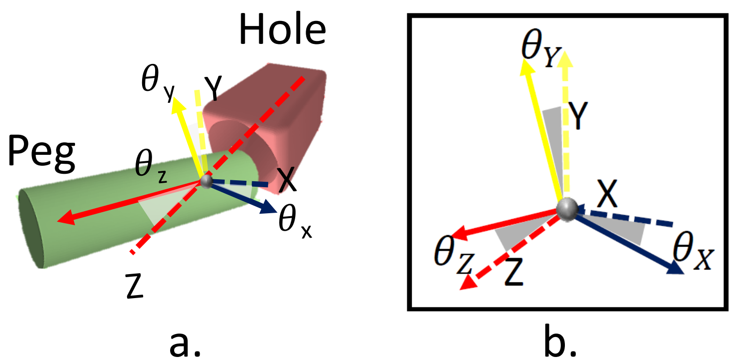


Figure 3.3: (a) User performance metric for computing misalignment error between the longitudinal axes of the peg and hole. (b) We evaluate the misalignment along the Z axes of both shapes.

3.5.4 Data Collection & Metrics

For each trial performed by the participants, we recorded (a) the raw event log containing time-stamped position and orientation for each 3D printed peg and hole shape, as well as the controller proxies for each Unity frame, (b) user feedback, and (c) live video of the participant. We specifically evaluate the motion of the peg as the goal is to dock it inside the hole. For this, we used four different metrics to compare our interfaces, namely, (1) bi-variate misalignment-time metric, (2) path deviation metric, (3) path efficiency, and (4) average path length.

3.5.4.1 Bi-variate misalignment-time Metric — (M, T)

Typically, in 3D manipulation and docking tasks, most current literature measures some form of accuracy (e.g. proximity and orientation alignment of the user-manipulated shape to a target spatial configuration) as well as the amount of time taken to complete the manipulation task [200]. Furthermore, these two metrics are often treated independently. However, we observed that, given sufficient time, most users are able to assemble the peg into the hole regardless of the interface. Therefore, there is a common ceiling for accuracy that is independent of the treatment (the interface in our case). In fact, our preliminary analyses showed that there was no significant difference in accuracy across the two interfaces. Therefore, we

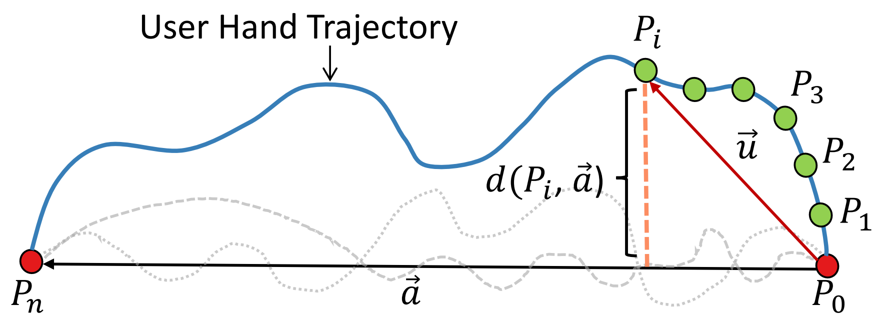


Figure 3.4: User performance metric [16] for computing path deviation and co-efficient of performance with respect to shortest path between the end points of the user's trajectory in 3D space.

adopted a bi-variate performance measure [102, 201] comprising of alignment error (signifying the task accuracy) (Fig. 3.3) and the time taken to complete the task. The misalignment M is simply the angle θ (in radians) between the Z axes of the peg and hole.

3.5.4.2 Path Deviation — Dev (Motor Strategy)

Simply measuring the accuracy of the final outcome of the task leads to a loss of information regarding the process (how users moved their arms and hands while performing the manipulation). Specifically for motion analysis, it is crucial to have a metric that quantifies the motor strategies in precise spatial interactions. In order to compare the precise manipulation actions and strategies across the two study configurations, we use the path deviation metric (Fig. 3.4), which is defined as the average of the Euclidean distance of each point P_i on the user's trajectory to a straight line $\vec{a}$ joining the end points of the trajectory [16]. This metric is primarily used from the perspective of precise motor movements in medical surgery tasks which demand high dexterity, hence, suitable for our analysis. Geometrically, the straight line segment between the two end points signifies the shortest and most direct route from the initial position of the peg to its final placement in the hole. Therefore, path deviation represents the amount of additional effort put in by the user in reaching the target position by deviating from a straight-line path. The lower the deviation, the better the manipulation process. Mathematically, path deviation is given by:

$$Dev = \frac{1}{n}\sum_{1}^{n} d(P_i, \vec{a}). \tag{3.1}$$

Here, P_i is the point at the i^{th} frame in user's trajectory and $d(P_i, \vec{a})$ is the projection of P_i on the vector $\vec{a}$ joining the start and end points of the trajectory.

3.5.4.3 Co-efficient of Performance — Perf (Spatial Effort)

The co-efficient of performance metric is analogous to the path efficiency metric primarily used for high precision medical surgeries and medical rehabilitation [202, 203, 16]. It is defined as the ratio of total path length of the user's trajectory to the length of the straight line between the end points of the trajectory (Fig. 3.4). While Path Deviation quantifies the digression in *motor strategy* and *path planning* from a straight line trajectory, the Co-efficient of Performance signifies specifically the *user movement* in 3D space. The straight line distance geometrically signifies the *shortest continuous motion* of the peg to its final placement in the hole. Therefore, co-efficient of performance represents the amount of additional physical distance covered by the user, thus, the spatial effort in reaching the target position. The lower the co-efficient of performance, the better the spatial manipulation control. Mathematically, the co-efficient of performance is given by:

$$\textit{Perf} = \frac{\sum_{2}^{n} \|P_i - P_{i-1}\|}{\|P_n - P_0\|}. \tag{3.2}$$

Here, P_{i-1} and P_i represent the successive points on user trajectory, whereas P_0 and P_n represent the start and end points of user trajectory.

3.5.4.4 Average Path Length — Len (Motor Strategy and Spatial Effort)

The aforementioned two metrics — Dev and *Perf* evaluate user performance in terms of user's motor strategy and spatial effort. Our final metric is an absolute representation of these trajectories, which is defined as the average of the sum of Euclidean distances between

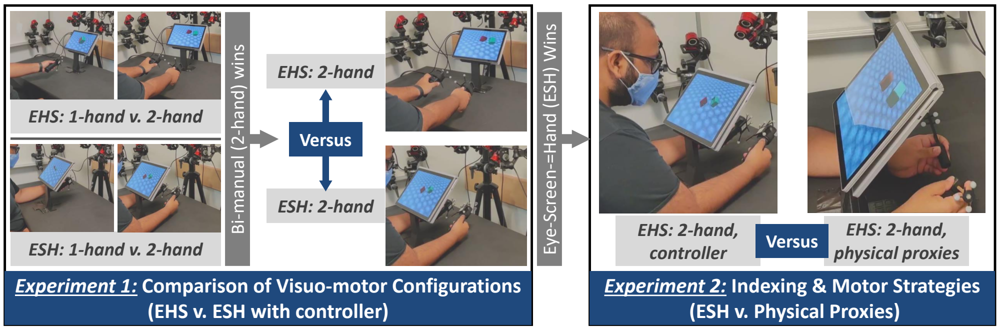


Figure 3.5: A flowchart illustrating our experiment design in terms of the experiments conducted and evaluations within each experiment.

successive points on the user's trajectory across multiple trials for a given user. Here, the average path length presents a realistic picture of the user's actual physical motion (planning and spatial effort) in typical spatial manipulation scenarios. The lower the path length, the lower is the spatial movement performed by the user and as a result, lower arm fatigue.

$$Len = \frac{1}{n}\sum_{2}^{n} \|P_i - P_{i-1}\|. \tag{3.3}$$

Here, P_{i-1} and P_i represent the successive points on user trajectory.

3.6 Experiment 1: Comparison of Visuo-Motor Configurations

Our primary goal in this experiment was to study user performance in *precise bi-manual manipulations* across our two visuo-motor configurations (*EHS* and *ESH*). While bi-manual spatial manipulation actions have shown to perform better across different MR systems (Section. 2.4), we wanted to confirm the same for SUIs in the peripersonal space. We designed a (2 x 2) between-subjects experiment such that each participant performed both the uni-manual and bi-manual variants of the peg-in-hole task only for one visuo-motor configuration. Out of 33 participants, we equally distributed 22 participants across the two experimental setup configurations.

3.6.1 Uni-manual v. Bi-manual Performance

First, we compare uni-manual (one-handed) and bi-manual (two-handed) control for each of the visuo-motor configuration (ESH and EHS) (Figure. 3.1) affects user-performance for a peg-in-hole docking assembly task. In particular, we wanted to confirm if our findings corroborate with past literature. We performed Shapiro-Wilk test to verify normal distribution of the collected user data samples and further, conducted hypothesis testing using Kruskal-Wallis test which is the non-parametric statistical equivalent of one-way ANOVA test.

In this specific case, comparing misalignment error and completion time alone showed significant difference in user-performance between uni-manual and bi-manual tasks across the two interfaces. For the Eyes$\rightarrow$ Hands$\rightarrow$ (EHS) configuration, the average misalignment was about 15° for the bi-manual approach as opposed to 30° for the uni-manual approach across all shapes and sizes. However, higher misalignment were observed for both sizes of the the trapezoid. We also observed a difference of 5 to 6 seconds in the docking time between uni-manual and bi-manual input modes, where the latter performed better. We observed similar results, in case of Eyes$\rightarrow$ Screen$\rightarrow$ Hands (ESH) configuration, where the the misalignment was about 12° for the bi-manual approach as opposed to 24° for the uni-manual approach. Here, the docking time difference here was slightly in the lower range of 3 to 4 seconds.

In addition to the quantitative assessment, we analyzed the NASA-TLX results and user preference was inclined towards the bi-manual approach overall. In whole, we observed bi-manual approach performing better across our two setup configurations (EHS and ESH), thus, confirming our hypothesis. Based on these findings, we further compare between the visuo-motor configurations for the bi-manual input mode on the basis of user performance and user preference.

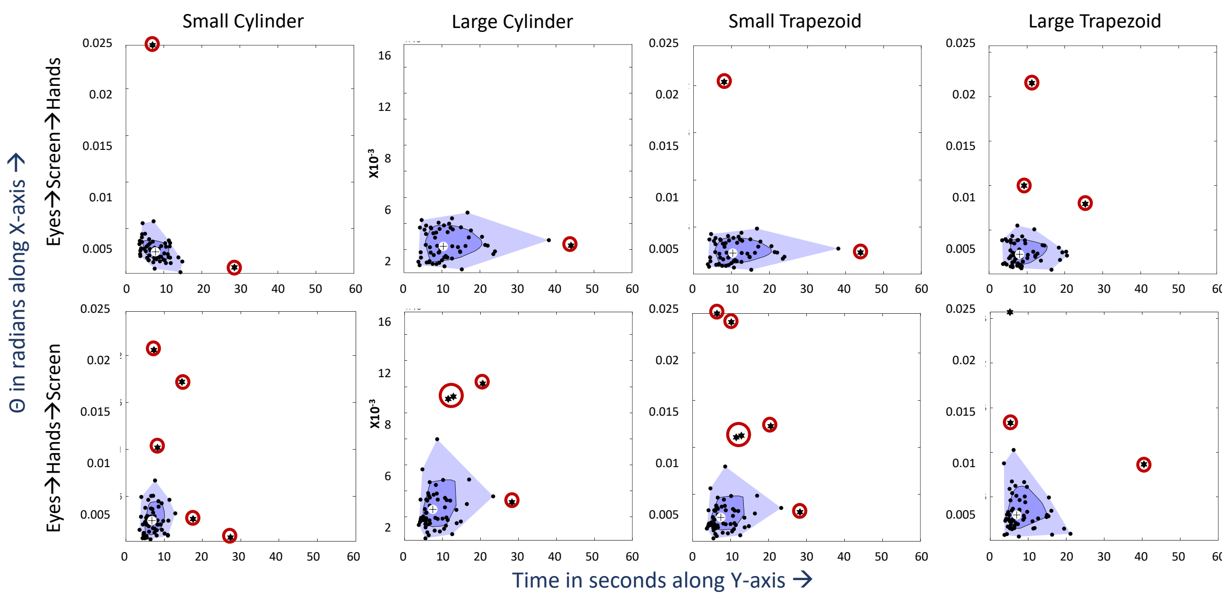


Figure 3.6: (Plots scaled for readability) Bagplot representation for precise bi-manual user actions across the two visuo-motor configurations — eyes→ screen→ hands (ESH) and eyes→ hands→ screen (EHS) for small and large sizes of cylinder and trapezoids. X-axis represents task completion time in seconds between [0,60] and the Y-axis represents the misalignment error as θ in radians. A cross near the center of a graph marks the depth median, the point with highest possible Tukey depth. The inner polygon represents the boundary, and the outer polygon represents the fence. The asterisks marked by red circles represent the outliers. (*Lower Tukey depth median (TD) and inner polygon area (B) are better.*)

3.6.2 *Eyes→ Hands→ Screen* vs. *Eyes→ Screen→ Hands* for Bi-manual Interactions

Based on our confirmation that bi-manual tasks were better performed by users for each visuo-motor configuration, we now evaluate our two visuo-motor configuration prototypes for the bi-manual input modes. Here, we intend to observe and understand precise spatial interactions performed close to our body i.e. in the peripersonal space from the point of bi-manual control. Our preliminary analysis showed very close accuracy and docking times as the participants were allowed to complete the docking. Therefore, we compare using the metrics defined in Section 3.5.4.

3.6.3 Results: EHS or ESH for precise manipulation ?

Similar to the previous comparison, we performed Shapiro-Wilk test to verify normal distribution of the collected user data samples. This was followed by hypothesis testing using Kruskal-Wallis test. We denote the mean and standard deviation for a given data sample by μ and σ respectively for all statistical evaluations.

3.6.3.1 User Performance: Bi-variate misalignment-time

In this metric, we make comparisons across the two visuo-motor configurations for each shape and size. We represent this comparison in the form of an array of bagplots [204] which is a bi-variate representation of the box-plot. Bag-plots are a bi-variate representations of the uni-variate Box-plots. Each bagplot is a convex polygon that is summarized by the Tukey depth median (TD), its coordinates (M), and the areas of the boundary (B) and the fence representing the location, spread, skewness, and outliers of the dataset respectively. Lower TD and B indicate lower spread, and therefore better correlation.

Across all shapes and sizes, we observe a consistently lower (Fig. 3.6) inner polygon area and Tukey depth median for the ESH [small cylinder: *TD: 9, M(7.7, 0.002), B: 0.011*; large cylinder: *TD: 7, M(6.36, 0.001), B: 0.011)*; small trapezoid: *TD: 5, M(10.63, 0.002), B: 0.310*; large trapezoid: *TD: 2, M(8.05, 0.002), B: 0.020*] when compared to EHS configuration [small cylinder: *TD: 15, M(6.78, 0.002), B: 0.014*; large cylinder: *TD: 14, M(5.55, 0.001), B: 0.015*; small trapezoid: *TD: 10, M(8.69, 0.001), B: 0.025*; large trapezoid: *TD: 7, M(8.61, 0.001), B: 0.033*]. **This indicates a relatively lower skewness in misalignment-time correlation for the Eyes→ Screen→ Hands, thus, better user performance.**

3.6.3.2 User Performance: Path Deviation Dev

In this comparison, ESH (small cylinder - μ*: 0.037m,* σ*: 0.014m*; large cylinder - μ*: 0.037m,* σ*: 0.015m*; small trapezoid - μ*: 0.034m,* σ*: 0.016m*; large trapezoid - μ*: 0.038m,* σ*: 0.013m*) has a significantly lower path deviation than CVR (small cylinder - μ*: 0.055m,* σ*: 0.022m*;

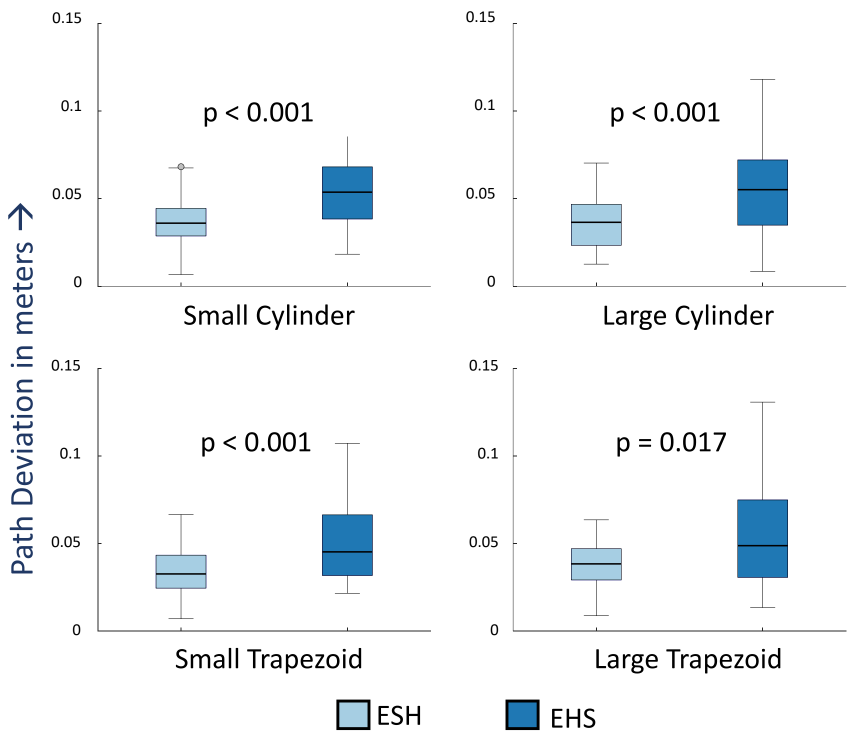


Figure 3.7: User performance evaluation between Eyes→ Screen→ Hands (ESH) and Eyes→ Hands→ Screen (EHS) for **path deviation (*Dev*)** in meters. ESH has an overall lower path deviation that EHS.

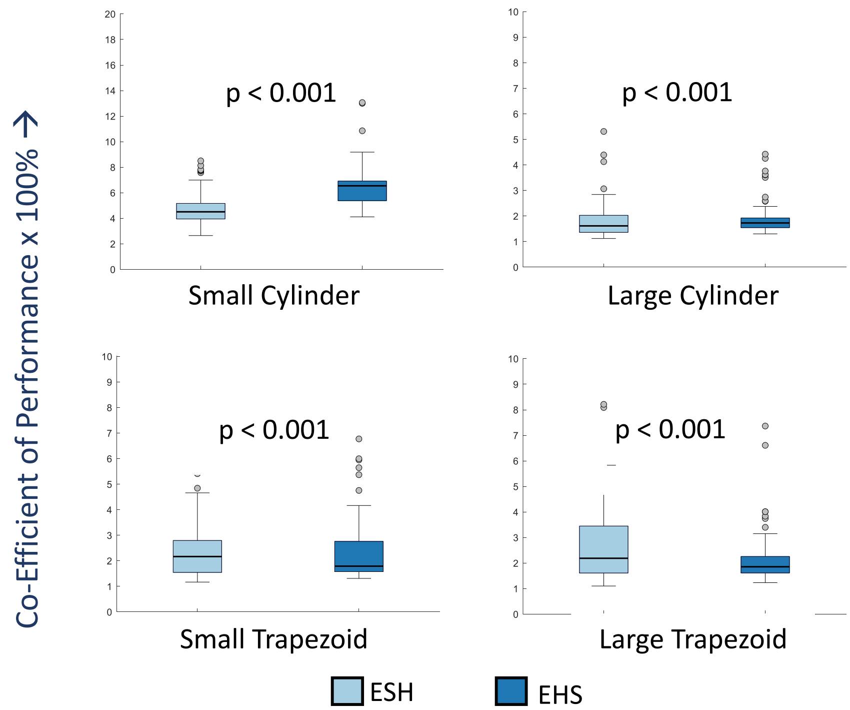


Figure 3.8: User performance evaluation between Eyes→ Screen→ Hands (ESH) and Eyes→ Hands→ Screen (EHS) for **co-efficient of performance (*Perf*)** in percentage. Lower *Perf* is better.

large cylinder - μ: *0.055m*, σ: *0.023m*; small trapezoid - μ: *0.051m*, σ: *0.023m*; large trapezoid - μ: *0.051m*, σ: *0.025m*) across all shapes and sizes (Fig. 3.7). **This indicates that having a screen before their hands (ESH) and further close to their body allowed for users to come up with efficient, shorter, and direct motor strategies than interacting with distal displays (EHS).**

3.6.3.3 User Performance: Co-efficient of Performance (Perf)

Here, across all shapes and sizes, there was no significant difference in path efficiencies between ESH (small cylinder - μ: 1.910, σ: 0.816; large cylinder - μ: 1.842, σ: 0.779; small trapezoid - μ: 2.495, σ: 1.469; large trapezoid - μ: 2.706, σ: 2.310) and EHS configuration (small cylinder - μ: 2.416, σ: 0.658; large cylinder - μ: 1.946, σ: 0.699; small trapezoid - μ: 2.638, σ: 1.982; large trapezoid - μ: 2.388, σ: 1.735) (Figs. 3.8). However, the mean path

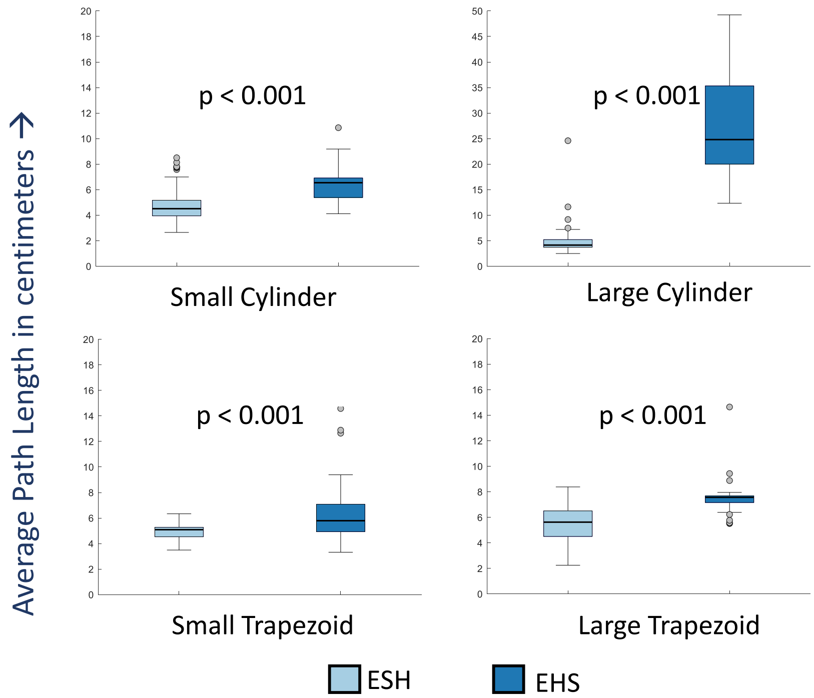


Figure 3.9: User performance evaluation between Eyes→ Screen→ Hands (ESH) and Eyes→ Hands→ Screen (EHS) for **average path length (*Len*)** in centimeters.

efficiency for ESH was found to be lower for most shapes except the smaller trapezoid.

3.6.3.4 User Performance: Average Path Length (Len)

In this pairwise comparison, the average path length for ESH was significantly lower (Fig. 3.9) for all shapes (small cylinder - μ*: 42.297 cm,* σ*: 14.52 cm*; large cylinder - μ*: 41.279 cm,* σ*: 15.347 cm*; small trapezoid - μ*: 57.163 cm,* σ*: 32.944 cm*; large trapezoid - μ*: 55.3806 cm,* σ*: 46.2916 cm*) as compared to CVR. **To summarize, users took a relatively shorter and a lower effort path when they interacted after the screen.**

Overall, our statistical analysis show better user performance for the Eyes→ Screen→ Hands configuration. This is also representative of how humans make fine and precise motor movements in the peripersonal from the point of a co-located visuo-motor space.

sectionExperiment 2: Indexing and Motor Strategies Given that proprioceptive and kinesthetic control are crucial to 3D modeling and design tasks (section 2.3) [61], our second experiment is focused on understanding tactile and kinesthetic control for precise spatial manipulation in the peripersonal space. Building on the results of our first experiment, our idea here is to take the *ESH* configuration that showed promising results and deeply study the physical indexing and motor strategies in precise manipulation. Research in "*psychology, neuroscience and HCI discuss that depth perception distortion is a common problem in virtual reality*" [62] This impedes the ability to make fine spatial control; as a result, object manipulation becomes a difficult and *high effort task*. Therefore, we conduct a systematic comparison between the motion-tracked hand-held controller and $3D$ printed physical proxies of the study shapes as the input modes to understand if mapping the geometry of the virtual and physical shapes improves motor control. We recruited the remaining 11 participants for this study.

3.6.4 Design and Tracking of Physical Proxies

The physical proxies are designed as with the same dimensions as the virtual 3D objects (Fig. 3.2(c)). While the hand-held controllers used a power grasp for fine motor control at the wrist level, the physical proxies were designed to afford *two to three finger grasp* [199, 198], thus, allowing precision at the finger tip level.

3.6.5 Results: The Effect of Kinesthetic and Proprioceptive Control on Precise Actions

Similar to the previous comparison, we performed Shapiro-Wilk test to verify normal distribution of the collected user data samples. This was followed by hypothesis testing using Kruskal-Wallis test.

3.6.5.1 User Performance: Bi-variate misalignment-time

We observed that ESH Controller variant performs better than the ESH physical proxies only for larger shape variants (Fig. 3.10) of cylinder [*TD: 7, M(6.36, 0.001), B: 0.011*] and

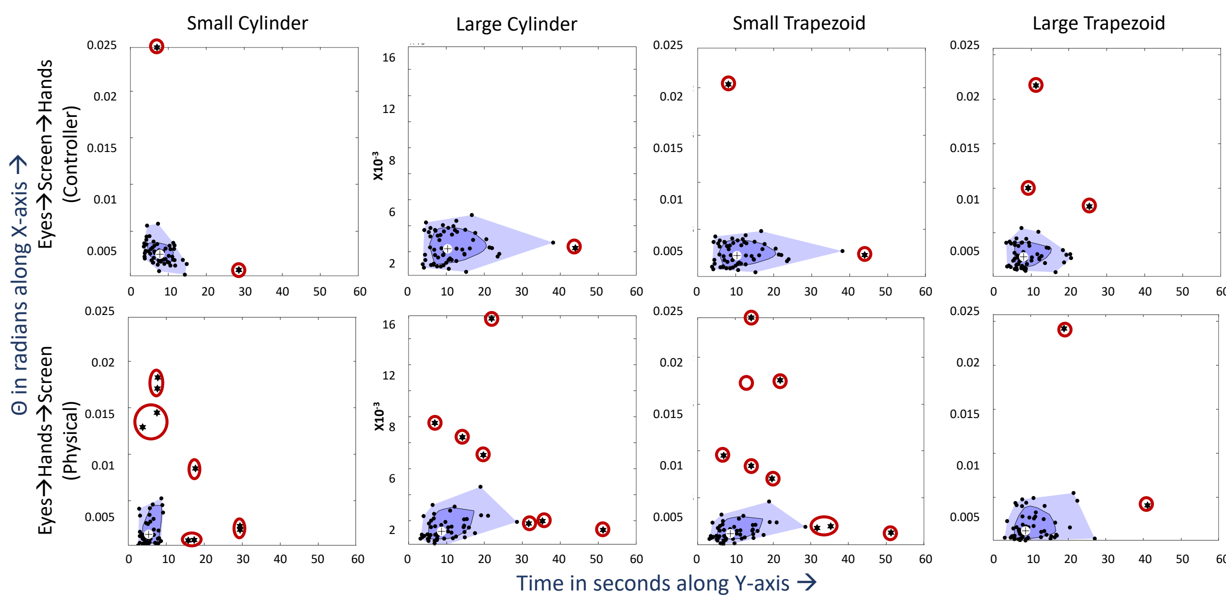


Figure 3.10: (Plots scaled for readability) Bagplot representation for precise bi-manual user actions across the between controller and physical proxies variants of Eyes→ Screen→ Hands (ESH) configuration for small and large sizes of cylinder and trapezoids. X-axis represents task completion time in seconds between [0,60] and the Y-axis represents the misalignment error as θ in radians. A cross near the center of a graph marks the depth median, the point with highest possible Tukey depth. The inner polygon represents the boundary, and the outer polygon represents the fence. The asterisks marked by red circles represent the outliers. (*Lower Tukey depth median (TD) and inner polygon area (B) are better.*)

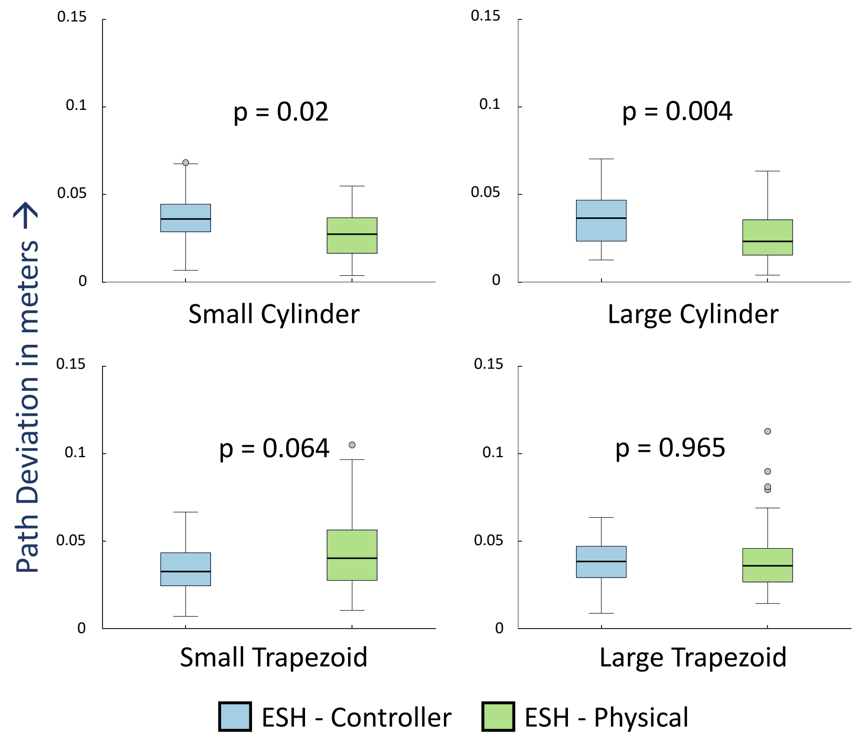


Figure 3.11: User performance evaluation between controller and physical proxies variants of Eyes→ Screen→ Hands (ESH) configuration for **path deviation (*Dev*)** in meters. The physical proxes variant has a lower path deviation for the cylindrical peg-and-hole pairs.

trapezoid [*TD: 2, M(8.05, 0.002), B: 0.020*] shapes.

3.6.5.2 User Performance: Path Deviation Dev

In this pairwise comparison, we observe that the path deviation for the ESH Physical Proxies variant (small cylinder - *μ: 0.029m, σ: 0.022m*; large cylinder - *μ: 0.029m, σ: 0.025m*) interface is significantly lower than the ESH Controller variant (*small cylinder - μ: 0.037m, σ: 0.014m*; large cylinder - *μ: 0.037m, σ: 0.015m*) for both cylinder sizes (Fig. 3.11), whereas, for the trapezoidal prisms, there is no significant difference between the physical and CMWS having p-values of 0.064 and 0.965 for smaller and larger sizes respectively. This indicates that the trapezoidal shapes are equally difficult to align with our without tactile perception.

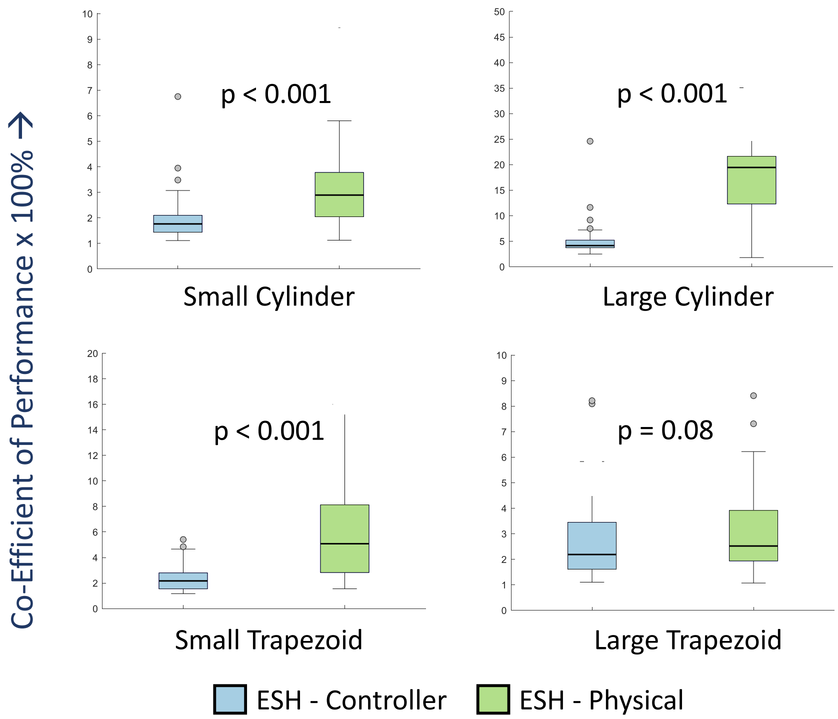


Figure 3.12: User performance evaluation between controller and physical proxies variants of Eyes→ Screen→ Hands (ESH) configuration for small and large sizes of cylinder and trapezoids for for **co-efficient of performance (*Perf*)** in percentage. Lower *Perf* is better.

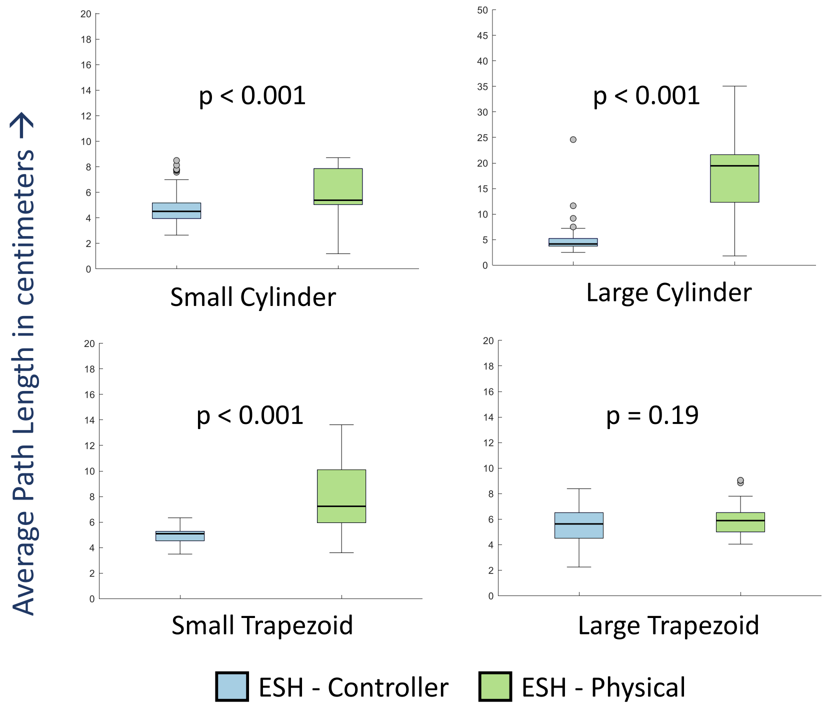


Figure 3.13: User performance evaluation between controller and physical proxies variants of Eyes→ Screen→ Hands (ESH) configuration for small and large sizes of cylinder and trapezoids for for **average path length (*Len*)** in centimeters.

3.6.5.3 User Performance: Co-efficient of Performance (Perf)

Here, the path efficiency was found to be significantly higher (Fig. 3.12) for the ESH Physical Proxies variant (small cylinder - μ: *4.048*, σ: *1.733*; large cylinder - μ: *3.774*, σ: *3.456*; small trapezoid - μ: *7.686*, σ: *10.167*; large trapezoid - μ: *3.799*, σ: *3.531*) across all shapes and sizes when compared to the ESH Controller variant (small cylinder - μ: *1.910*, σ: *0.816*; large cylinder - μ: *1.842*, σ: *0.779*; small trapezoid - μ: *2.495*, σ: *1.469*; large trapezoid - μ: *2.706*, σ: *2.310*). Therefore, manipulation through tactile and proprioceptive control increased spatial efforts as the participants could feel the shapes and their edges, faces, and other geometric features.

3.6.5.4 User Performance: Average Path Length (Len)

In this pairwise comparison, the average path length was significantly lower (Fig. 3.9) for the ESH Physical Proxies variant for the cylinders (small cylinder - μ: 35.487 cm, σ: 32.354 cm; large cylinder - μ: 35.567 cm, σ: 29.161 cm) and significantly higher (Fig. 3.9) for the small trapezoid (μ: 69.433 cm, σ: 58. 91 cm). This can be attributed to the sharp geometry of trapezoids and higher probability for shaper interference during docking.

Overall, we observed significant improvement in user performance when asked to interact with physical proxies of the virtual shapes as an input. It led to the improvement of the accuracy-time correlation, minimal path deviation, and average path length. Surprisingly, the co-efficient of performance was poor for the ESH Physical Proxies variant which would need further analysis of user performance.

3.7 User Feedback & Video Analysis

In our final qualitative analysis, we first aim to report the users' feedback to each of our visuo-motor configurations, uni-manual and bi-manual input modes, and their experience with the physical proxies. More importantly, we present a detailed video analysis to report on what types of movement patterns and grasping strategies were observed across the different interfaces (ESH, EHS, and physical proxy-based interaction).

3.7.1 User Response to Task Load

We collected NASA-TLX [205] scores from participants after each interaction approach (uni-manual and bi-manual) for each experiment across all interfaces. Alongside, we also collected open-ended user feedback for 1584 trials performed by all 33 participants. We collected additional feedback through user survey regarding users' perception of accurate and precise spatial movements (Fig. 3.14 (g) (h)).

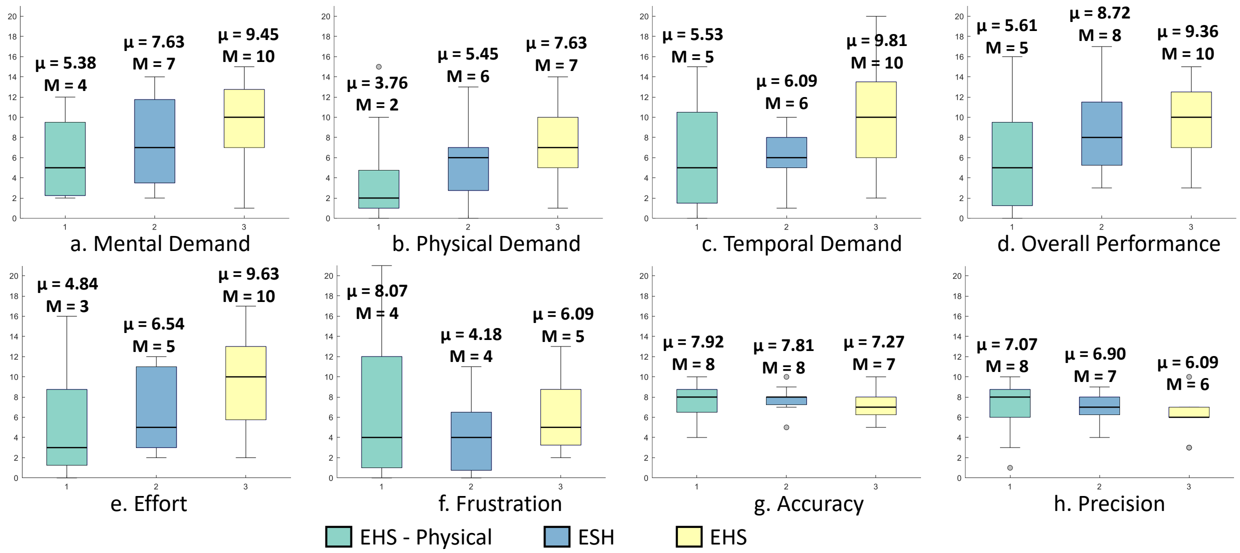


Figure 3.14: [a - f] NASA-TLX comparison across ESH - Physical Proxies, ESH - Controller, and EHS interfaces for precise bi-manual actions. The Y-axis represents the rating scale from [0,21] where a lower rating is better for all evaluation parameters; [f, g] User rating on accuracy and precision of their spatial actions across the three interfaces for controlling the peg and hole. We denote the mean and median for a given data sample by μ and M respectively.

3.7.2 User Response to Visuo-Motor Configuration

Most participants found ESH to be intuitive and easy to adapt for manipulating spatial objects using the physical shapes as well as the controllers as the input modalities when compared with EHS configuration. For ESH with controller, one user stated: "*It felt intuitive and natural to control the objects behind the screen and was able to manipulate as I would do in the absence of the screen.*" In case of the physical proxies in ESH, participants felt the manipulation to be "*direct*" and "*relatable*" to the visual feedback. However, for EHS, most users confirmed a "*lack of steadiness*" in their hand movements. This is confirmed by the higher path deviation (Dev) observed in EHS compared to physical and ESH interfaces (Fig. 3.7). We observe an overall user preference in favor of the physical interface, followed by ESH, and EHS ranked last (Fig. 3.14 (a) - (f)). Users' survey responses for the three interfaces resulted in very close mean scores.

3.7.3 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* [206, 207, 208] 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* [209, 210], the qualitative feedback collected from the participants provided interesting insight on the role of fatigue for spatial manipulation across both EHS and ESH. While the duration per trial was short enough to not cause any hand fatigue, users in the EHS group expressed discomfort about the physical stance for performing the docking task which resulted in unsteady hand movements. As a result, users rested one of their hands, mostly the one controlling the hole, on a flat surface while performing spatial manipulation. However, the co-located visuo-motor space in ESH helped mitigate the physical exertion, fatigue, and discomfort. This is confirmed by shorter average path length in ESH (Fig. 3.9).

3.7.4 Indexing & Motor Strategy Analysis

Our quantitative results found the ESH setup performing better than the EHS setup. We further conducted a preliminary analysis of the peg-in-hole assembly across different trials, shapes, and their respective sizes for all participants. In this analysis we highlight some key and commonly observed motor strategies for coarse and fine spatial manipulations across all user trials, the effect of learnability on these strategies for a given participant, and the relationship between this analysis and the observations we make in the quantitative results. We discuss the analysis keeping the following key aspects in mind:

3.7.4.1 Evolution of Strategies

Each user trial lasted approximately for $5 - 6$ seconds on an average and each study took about XYZ minutes. Due to the short duration of each user trial, we analyzed the video at normal (60fps), 0.5x (30fps), anb 0.25x (15fps) speeds to make a clearer sense of motor movements articulate by the users at the wrist-level. To note, our study setups and tasks are a protoype towards the Clockmaker's Workspace where the goal is to enable precise motor control at the finger level. We identified some key motor strategies followed commonly by all users across all trials such as:

Step 1. **Lifting** the peg and hole $3D$ shapes vertically from their default position on the virtual ground. We mapped the tracking of physical and virtual space such that the controllers are also on a flat surface as the virtual shapes in the virtual environment.

Step 2. **Aligning** the peg-and-hole by rotating the shapes about either transversal axes. The shapes are aligned such that the flat surfaces that match during the assembly are opposite to each other.

Step 3. **Positioning** the shapes close to each other in $3D$ space by quickly bringing them closer after Step 2. The relative position of each shape is such that there is enough room for the user to make fine rotational as well as translational adjustments before assembling the two shapes.

Step 4. A **Frame of Reference** is established in $3D$ space by fixing the position of the hole to help insert the peg into it. In fact, the participants rotate the peg for an optimal viewing as a visual assistance to dock the peg

Step 5. Finally, **Docking** of two shapes happen when the peg is slowly and carefully inserted into the hole. In most case the authors made fine rotational adjustments about the longitudinal axes of each shape while moving closer to the hole.

While the aforementioned is a general approach followed by most participants, we did observe an *evolution of strategy* as each user progressed through the study. Especially in Steps 3 and 4 where for the first few trials users explored an optimal viewing angle for the hole and tested their docking strategies. Based on this trial-based approach, they either chose one of the previously tried strategies or formulate a newer strategy based on experiences from previous successes and failures in peg-in-hole docking. Thus, in addition to evolution of strategies within a given trial, we also observe an evolution across the entire duration of the study towards better user performance.

3.7.4.2 Motion Indexing

Motion indexing in video analysis is primarily used to identify and categorize a set of features observed while performing a certain action or a set of actions [211]. These features are further used in machine learning models and pattern recognition for motion classification, as well as, activity recognition applications [212, 213, 214, 215, 216, 217, 218]. While there are different approaches for indexing physical motions such as analyzing the limb joints individually (wrist, knee, ankle,.etc), posture of by a set of joints (lower or upper limbs), and gestures, our focus is on analyzing the upper limbs specifically from the elbow to the hands for coarse movements, and further, analyzing the wrist joint for fine manipulations. We discuss indexing pertaining to each shape as follows:

– Cylinder: As per our analysis of the docking process, cylinders for both small and large sizes were relatively easier to dock. One of the attributes is the presence of rotational symmetry and lack of sharp edges. The participants in most cases held the hole stationary and carefully inserted the peg into it with zero to minimal rotational adjustments at the wrist. However, fine translational adjustments were made to avoid any intersections with the hole. Although, it was relatively easier to make adjustments for the larger cylindrical shape.

– Trapezoid: In case of Trapezoid, both shape sizes required relatively more efforts in docking than their cylindrical counterparts. Indexing in this case was particularly observed for Steps 3 and 4 of motor strategy. Here, the hole was not only adjusted for an optimum viewing angle, but also adjusted that the triangular vertex is towards the user. In addition, the longest edge was also indexed for docking strategy. This involved users moving their wrist such that these actions mapped to rotation about the longitudinal axis of the trapezoidal shapes which was first performed for the hole followed by the peg in sequence as observed in Steps 4 and 5 of motor strategy.

3.7.4.3 Scalability of Interaction

Scalability of the interaction space is a qualitative representation of user performance metrics for each shape and size variant. Based on aforementioned analyses, there is a clear distinction on how shapes, rotational symmetry, and shape-sizes have an effect on the manipulation approach strategy. We build this discussion on two aspects as follows:

- Shapes: We observe that cylindrical peg-and-hole were relatively easier to dock than the the trapezoidal shape and this mainly alludes to the lack of rotational symmetry in the latter. As a result the strategy for aligning the trapezoidal peg and hole were more slow, careful, and fine-grained. While the speed at which the user got peg and hole across both shapes close as described in Step 2 of the motor strategy, the transitional phase from Steps 3 to 5 were relatively slower with deceleration closer to the hole.
- Size: We hypothesized that the shapes sizes would affect user performance where the smaller shapes would be slower and need more attention from the user to dock. In fact, smaller trapezoid was found to be relatively the most difficult shape to dock, followed by larger trapezoid and the larger cylinder being the fastest to dock.

3.8 Takeaway

The peripersonal space is a "*fuzzy*" volume surrounding the human (and animal) body that is interconnected with several overlapping spaces [175]. We presented an exploration of a peripersonal sub-space where precise manipulative work often takes place. This sub-space, which is crucial for tool use, has been largely ignored in current SUI and AR/VR literature. Our motivation is to closely investigate this space stemming from the fact that it is characterized by a unique confluence of very high bio-mechanical stability, stereoscopic acuity, tactile and haptic precision, hand and finger dexterity, and a tremendous opportunity for proprioception. This is also a space where tactile and visual perception are tightly coupled. In fact, the wrist-finger kinematics that is active in ESH is orders of magnitude higher in resolution in contrast to the shoulder-arm-palm kinematics invoked by current spatial user interfaces.

Our paper successfully demonstrated the promise of ESH interaction through a systematic study of interactive system configurations coupled with tangible proxies to serve as tools. Our results showed a clear improvement in manipulative performance, better efficiency, and motor strategies. However, our study is merely a starting point that shows a glimpse of the rich interaction and interfaces design space for fine grained tool usage in this high-resolution manipulation space. Below, we expand on the possibilities and implications of our study.

3.8.1 High-precision Tracking

While hand-held controllers are fairly common and robust, other technological aspects need careful consideration. This is especially true since current AR headsets are primarily designed for interaction at a distance. A major challenge that we faced was the lack of guidelines for implementing a close-range motion capture system for tracking high-precision interactions. This was not surprising since motion capture is predominantly used in room-sized environments. On the other hand, we also avoided the use of commodity cameras such as the Leap Motion [185], Kinect [186] and RealSense [184] since they do not offer as precise and smooth tracking capabilities with a limited tracking space measuring 0.5 ft x 0.5 ft x 0.2 ft [187]. Also, they offer limited accuracy having a high mean tracking error of 1.2mm [188] which stands insufficient for tracking hand-held objects with sub-millimeter tracking fidelity (our own study indicated at least 10^{-2} mm precision in measurements). Even though there has been a large body of work dedicated to hand and object tracking in the last few years, a completely new body of research is warranted for the development and standardization of object tracking at sub-millimeter scale.

3.8.2 Precision Tools & Proprioceptive Manipulation

From a kinematics standpoint, the movement and therefore manipulative ability enabled by the shoulder-arm-wrist complex is primarily responsible for *ballistic* actions [219] in the outer regions of the peripersonal space leading up to the extra-personal space (beyond arm's length). This is the space in which current AR/VR and SUI interactions are typically designed and studied. However, shoulder-arm-wrist kinematics is prone to singularities that are associated with coarse movements. In contrast, finger-level manipulations can afford to perform highly precise activities (such as hand-writing and use sharp and fine tools) because of the highly redundant degrees of freedom [220].

Our analysis revealed that while bi-manual manipulation is significantly better than uni-manual manipulation in physical interactions as expected [221, 222], both modes perform with similarly for ESH and physical configurations. This indicates that the efficacy with the controller system on account of several interesting factors such as constancy of controller geometry and size. Furthermore, our study showed that using the shape of the real object as opposed to generic controllers in ESH allowed users to work more effectively. Specifically, the inherent ability of the hand to quickly make fine manipulations, such as twisting the trapezoidal peg about its own axis for aligning with the hole, points to a need for tracked physical-digital proxies and tools for precise manipulation in ESH. Such tools that will afford fine-grained interactions (e.g. precise clay carving) virtual objects with precision that is unimaginable in current AR/VR systems. Secondly, our study also reinforces the need directional tactile feedback in these new tools that will inform the user of object proximity and orientation in ESH. While not as strong as force feedback, we believe it will play a significant role for high-precision interactions in intimate spaces where the sense of touch overshadows visual feedback in many cases [223].

3.8.3 Visual Feedback Technology

Generally, spatial user interfaces integrate medium to large interaction volumes [224] owing to task design conventions followed for decades and technological limitations of current hardware configurations. Here, the visual feedback of user actions is either through the HMD or on a larger display in front of the user. Our study in this work informs of distinct motor strategies adopted by the users based on the spatial configuration of the visual feedback — ("*eyes*⟶*screen*⟶*hand*") and ("*eyes*⟶*hand*⟶*screen*"). The most crucial challenge that we faced in this work was to configure a small-scale interaction space (2 ft x 2 ft x 1.5 ft) for high-precision manipulation tasks (SD: 0.035 mm tracking error) facilitating a steady and continuous manipulation motion. While our behind-the-display interaction approach didn't support a see through display feature, it facilitated a co-located visuo-motor space combining the user's proprioceptive bi-manually coordinated actions with a sub-millimeter error motion response in the virtual visual feedback. This visuo-motor coordination is supported by the relatively lower path deviation (Fig. 3.7 and average path length (Fig. 3.9) of ESH when compared with the non-immersive EHS configuration. Also, our participants found the former interface to be intuitive, natural, and steady for spatial manipulation. Let us consider user behavior for manipulating objects small enough to be held by a two-finger precision grip for highly skilled spatial manipulation tasks. In this case, the action-specific visual perception [26, 25] of manipulating such small objects will need co-locating the human motor zone with small-sized ultra-high resolution see-through displays. There is a promising research potential in leveraging 4K visual displays that mobile devices already posses for configuring AR and VR systems. We imagine scenarios closely resembling the actual clockmaker's space wherein user will be able to manipulate very small objects under high-resolution magnified views while working with hand-held precision tools.

3.8.4 Future Systems and Interactions for Clock-maker's Work-space

Human anatomy, object geometry and size, and input modes have a significant effect on the interaction space, which is reflected in the action performed. Profitt et al. [27] discuss how the visual perception of distances and sizes is affected by growing expertise in a given task. Witt et al [25] showed similar evidence for tool handling distance and its action-specific size perception owing to the type of task performed. On similar lines, our study showed that enabling precise manipulation with proxy controllers is actually a function of the system configuration (how the eyes, hands, and screen are located with respect to each other). Specifically, the ESH configuration allows for precise assembly of the peg in the hole as was the case with actual physical proxies. ESH also proved to be significantly better in manipulation efficiency and path deviation in comparison to the conventional VR system. Both of these observations show that enabling a closely integrated visuo-motor space enhances action-specific perception for close and distant spatial interactions. Our work points to a need for re-thinking existing spatial interactions — pointing, ray-casting, HOMER, .etc, and the economy of these actions expended during spatial interactions.

3.8.5 Need for New Evaluation Methodologies

High-precision manipulation tasks often require a higher-degree of hand-eye coordination whose effect can be seen in the motion trajectory of the action performed. However, most SUI literature to date focuses on metrics such as accuracy and completion time. While our initial attempts were on similar principles, we observed that using aggregated statistics for precision tasks offers virtual no insight on the user performance. To that effect, our current metrics based on minimally invasive surgery [202, 203, 16] (path efficiency and deviation) clearly demonstrated the correlation between user actions (how they moved) with their performance in the manipulation task. This allowed us to show that the hand-held controller serves as a better proxy for the real physical shapes in ESH than the conventional VR interface. However, manipulations beyond the wrist up to fingers are far more complex owing to a completely different kinematics. There is a significant body of research that is needed to create appropriate evaluation standards for ESH.

3.9 Conclusion

In this chapter, we presented the idea of how actions performed close to the body enable precise control in virtual spatial tasks. Our goal was to mainly systematically explore how interfaces designed to close space interactions can afford fine motor perception for manipulating virtual $3D$ objects, also, how they perform in comparison to existing SUIs where interactions happen at an arm's length. Thus, CMWS presents a broader perspective on how we can design future SUIs towards facilitating close-space interactions for fine perception, hand-eye coordination and intuitive interaction experience. In the following chapter we build upon this notion of proximity to action and investigate the role haptics in augmenting precise spatial control in spatial tasks.

4. KINESTHETIC METAPHORS FOR PRECISE SPATIAL MANIPULATION: A STUDY OF OBJECT ROTATION*

4.1 Overview

In this work, 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 aide 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.

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. With this mind, we discuss the algorithm design, setup configurations, and evaluation of our kinesthetic metaphors for precise spatial rotation in the following sections.

*This chapter is reprinted with permission from Mohanty, R. R., and Krishnamurthy, V. R. "Kinesthetic Metaphors for Precise Spatial Manipulation: A Study of Object Rotation." ASME. J. Comput. Inf. Sci. Eng. April 2021.

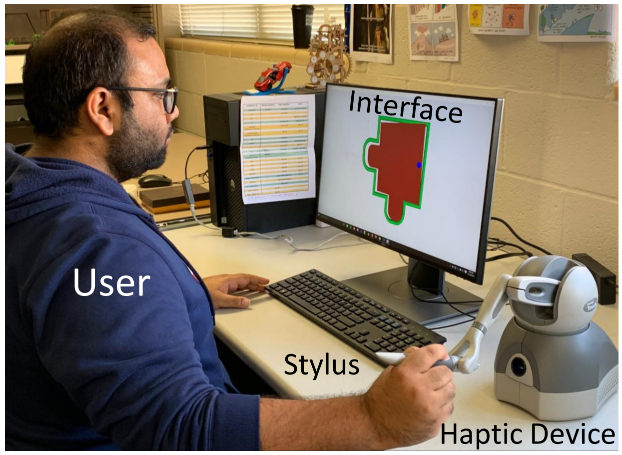


Figure 4.1: User Experiment Setup for Kinesthetic Spatial Rotation (Reprinted with permission from [225]).

4.2 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

4.2.1 Hardware

Our hardware setup (Fig. 5.1) 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 [130, 129, 128, 131], surgery, and motor-rehabilitation [226] 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.

4.2.2 Force Feedback for Rotation

Prior works [94, 95, 114, 96, 113, 97] 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, 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.

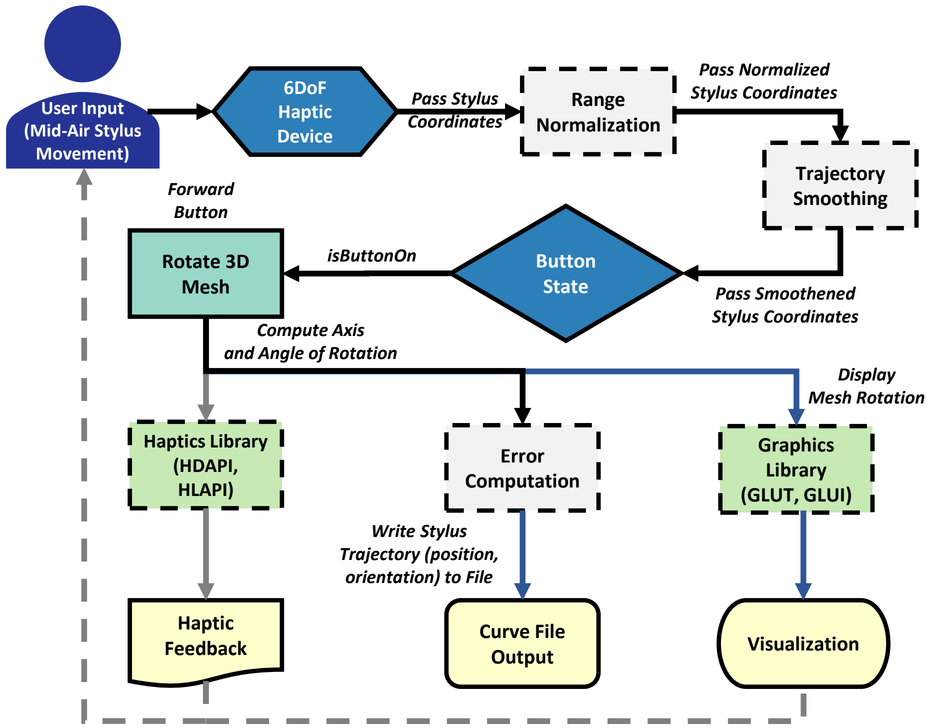


Figure 4.2: Software Architecture Diagram for Kinesthetic Spatial Rotation (Reprinted with permission from [225]).

4.2.3 Software Architecture

We classify our software architecture (Figure. 4.2) into two broad categories for processing user input as follows:

4.2.3.1 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:

$$\mathbf{v}_t = -1 + \frac{2(\mathbf{v}_t - [a_{min}, a_{min}, a_{min}]^T)}{a_{max} - a_{min}} \tag{4.1}$$

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

4.2.3.2 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 [227, 228]. 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:

$$\hat{\mathbf{v}}_t = \alpha \mathbf{v}_t + (1 - \alpha)\hat{\mathbf{v}}_{t-1} \tag{4.2}$$

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.

4.3 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*.

4.3.1 Global Rotation

4.3.1.1 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. 4.3(a)). This is, in spirit, similar to *Arc-Ball3D* proposed by Katzakis et al. [93].

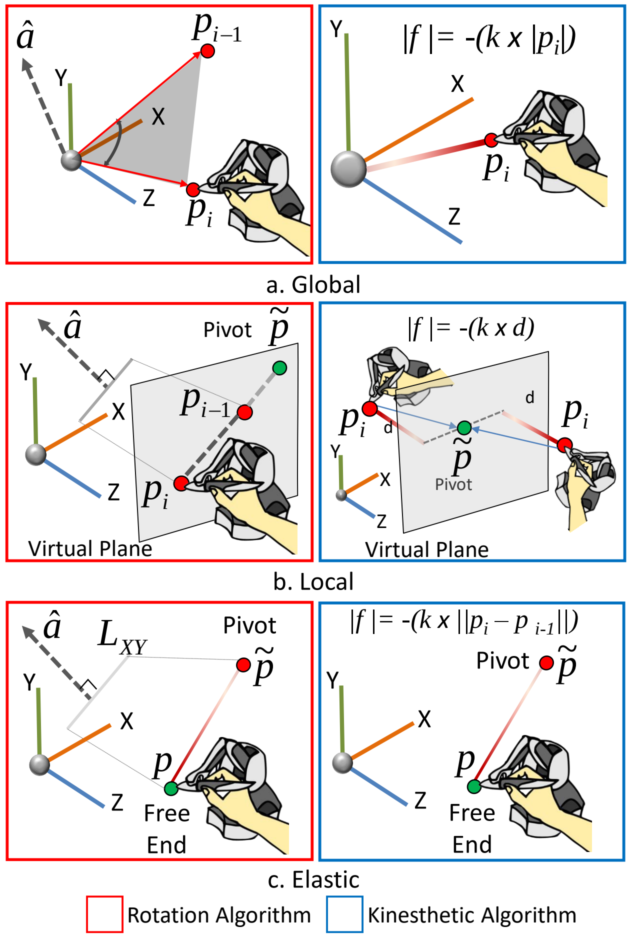


Figure 4.3: **Rotation**: Axis and angle are computed about the Global (G) origin (a), Axis and angle are computed using Local (L) stylus trajectory (c), and Axis and angle related to Elastic (E) length of the line about a fixed pivot (e). **Kinesthetic Feedback**: Force is computed radially outwards from the Global origin (b), Force is computed perpendicular to the virtual plane (d), Force is computed linearly proportional to the elastic length (f) (Reprinted with permission from [225]).

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

4.3.2 Linear Rotation

4.3.2.1 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. 4.3(b)). The constant c was determined from pilot experiments.

4.3.2.2 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 ($\mathbf{k}$) of 7.5 N/m provided a comfortable force feedback for the Linear rotation technique.

4.3.3 Elastic Rotation

4.3.3.1 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 [103], 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

Figure 4.4: Polygonal shapes used for evaluation tasks (Reprinted with permission from [225]).

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. 4.3(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.

4.3.3.2 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 ($\mathbf{k}$) of 3.2 N/m provided a comfortable force feedback range preserving the elastic perception in the current rotation technique.

4.4 Experiment

4.4.1 Implementation

Our hardware (Figure.5.1) 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.

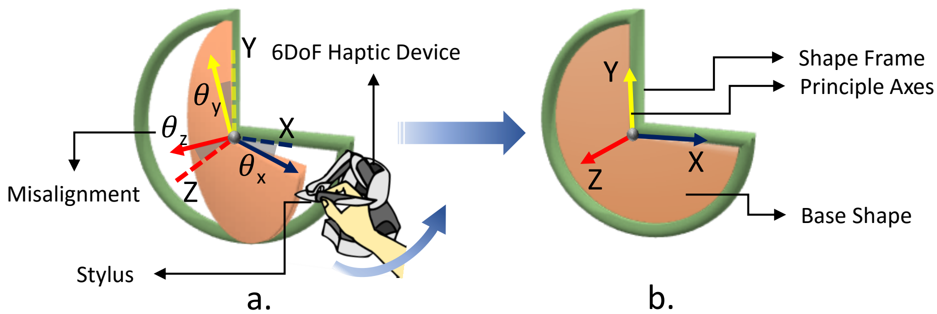


Figure 4.5: Evaluation task for kinesthetic spatial rotation interaction: (a) Default user-controlled interaction state with misaligned base shape, (b) Expected final state where the base and target shapes are aligned along their orientation vectors (Reprinted with permission from [225]).

4.4.2 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 [229] evaluating the rotation techniques between two 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 [230] between the control groups as well as the three rotation techniques.

4.4.3 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.

4.4.4 Procedure

Participants were shown a pair of shapes (Fig. 4.5) — 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. 4.4) 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. 5.1). 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 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 [205]. 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.

4.4.5 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 [231]. 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. 4.6). 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):

$$E_{deviation} = \frac{1}{2}\sin\theta \tag{4.3}$$

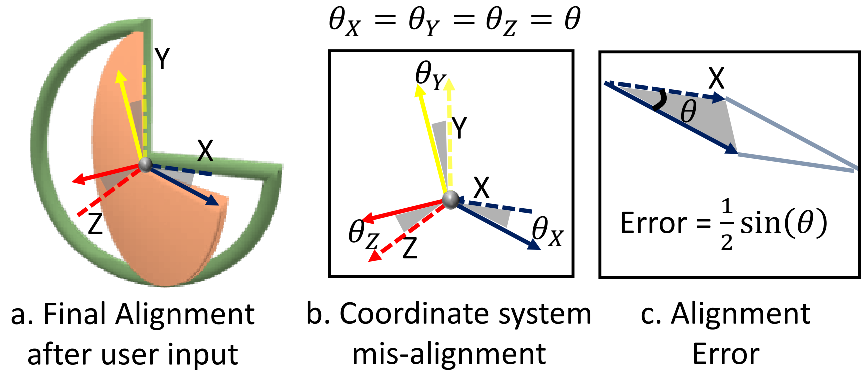


Figure 4.6: Error metric for the rotation tasks performed by the users (Reprinted with permission from [225]).

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).

4.5 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 4.5.2) 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 4.5.3). Finally, we shift our focus on comparing the three haptics-enabled rotation techniques for each of the four shapes (section 4.5.5).

4.5.1 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-

p-value \ Shapes	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	

Figure 4.7: 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 (Reprinted with permission from [225]).

parametric hypothesis testing to verify statistical significance between the two control groups as well as within the three rotation techniques.

4.5.2 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.
- **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

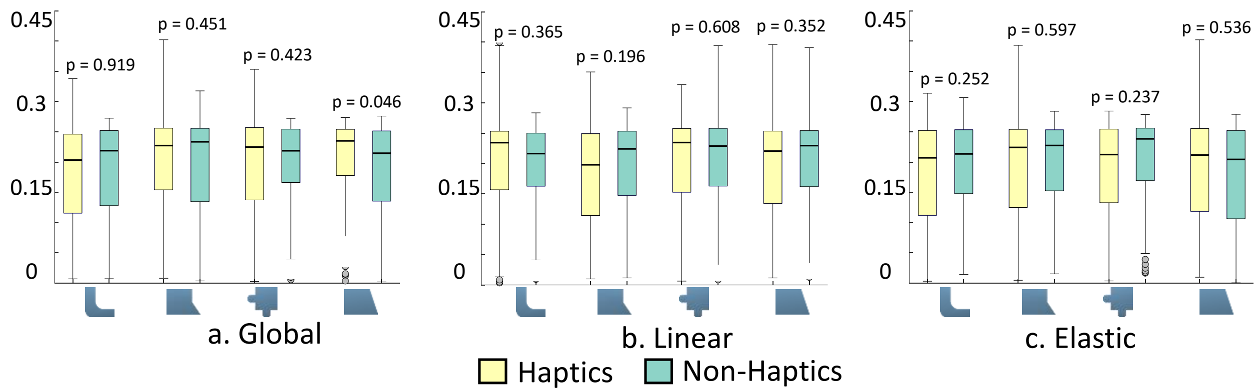


Figure 4.8: (a,b,c) **Error comparison along the x-axis** between Haptic and Non-Haptic treatments for Jay, Shoe, Puzzle and Trapezium shapes using Global, Linear and Elastic rotation techniques (Reprinted with permission from [225])

per our statistical analysis (Fig. 4.7), 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.

4.5.3 Pair-wise Haptic vs. Non-Haptic Comparison

4.5.3.1 User Performance

4.5.3.1.1 Misalignment Error: Here, we evaluate the misalignment error along each axis (Figures. 4.8, 4.9, 4.10) 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

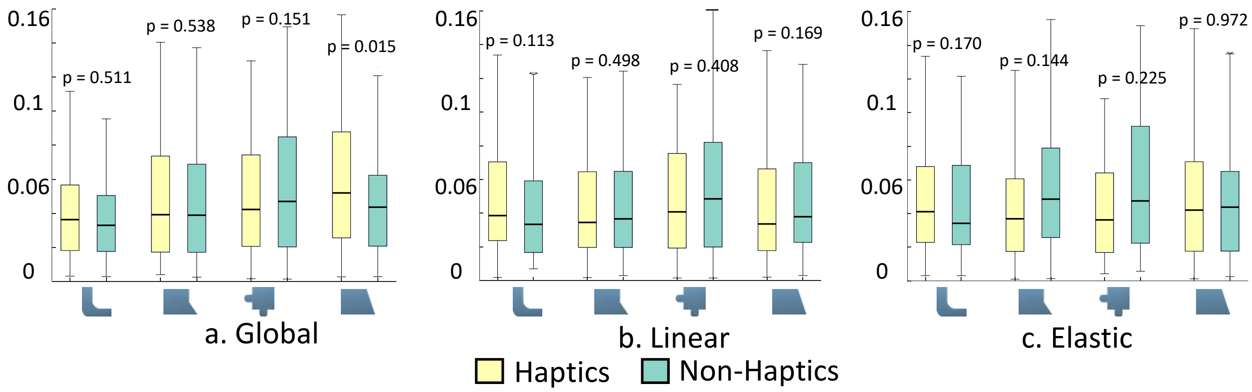


Figure 4.9: (a,b,c) **Error comparison along the y-axis** between Haptic and Non-Haptic treatments for Jay, Shoe, Puzzle and Trapezium shapes using Global, Linear and Elastic rotation techniques (Reprinted with permission from [225]).

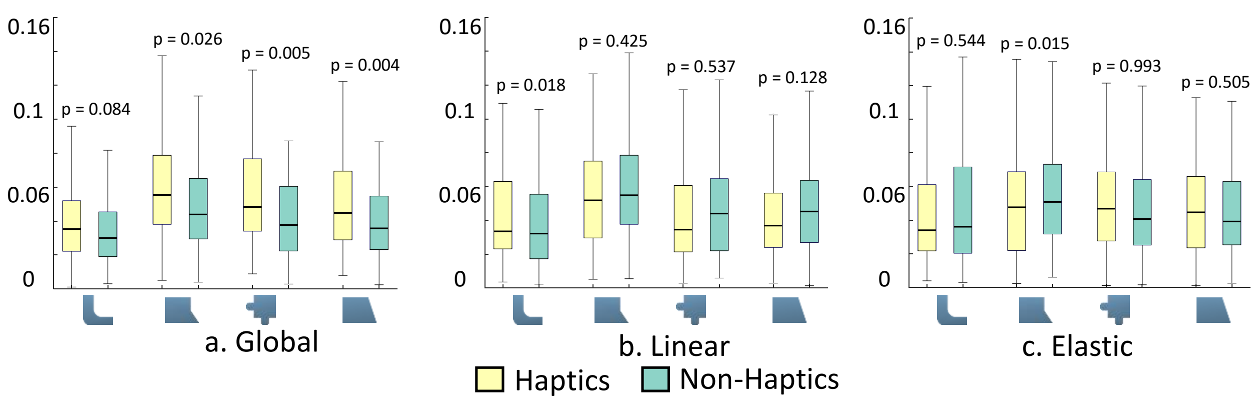


Figure 4.10: (a,b,c) **Error comparison along the z-axis** between Haptic and Non-Haptic treatments for Jay, Shoe, Puzzle and Trapezium shapes using Global, Linear and Elastic rotation techniques (Reprinted with permission from [225]).

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:

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*.

Completion Time:

Null(H_o): There is no significant difference between completion time in presence and

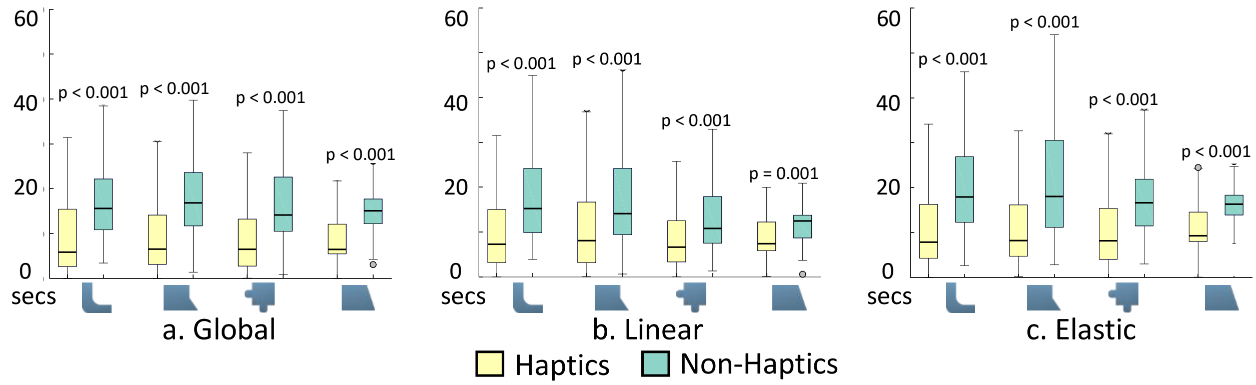


Figure 4.11: (a,b,c) **Completion Time** comparison between Haptic and Non-Haptic feedback for Jay, Shoe, Puzzle and Trapezium shapes using Global, Linear and Elastic rotation techniques (Reprinted with permission from [225]).

absence of haptic feedback for a given rotation technique.

Alternate(H_a): There is a significant difference between completion time 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 (Figure. 4.11). Further, due to non-normal nature of the data samples, we perform non-parametric Kruskal-Wallis test for hypothesis testing. We observed overall statistical significance (p-value ≤ 0.001) for all rotation techniques (Global, Linear, and Elastic) across 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

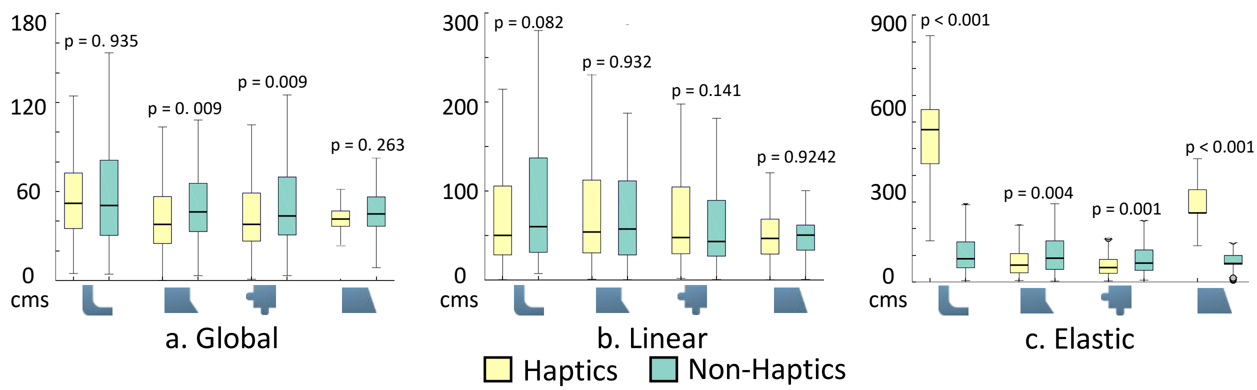


Figure 4.12: (a,b,c) Total physical **Stylus Path Length**(in centimeters) covered across each trial between Haptic and Non-Haptic feedback for Jay, Shoe, Puzzle and Trapezium shapes using Global, Linear and Elastic rotation techniques (Reprinted with permission from [225]).

length in presence and absence of haptic feedback for a given rotation technique.

Each data sample (Figure. 4.12) measuring the stylus path length per shape per rotation technique was evaluated to be non-normally distributed using the Shapiro-Wilk test. Further, due to non-normal nature of the data samples, we perform Kruskal-Wallis test for hypothesis testing. We observed statistical significance 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.

4.5.4 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.

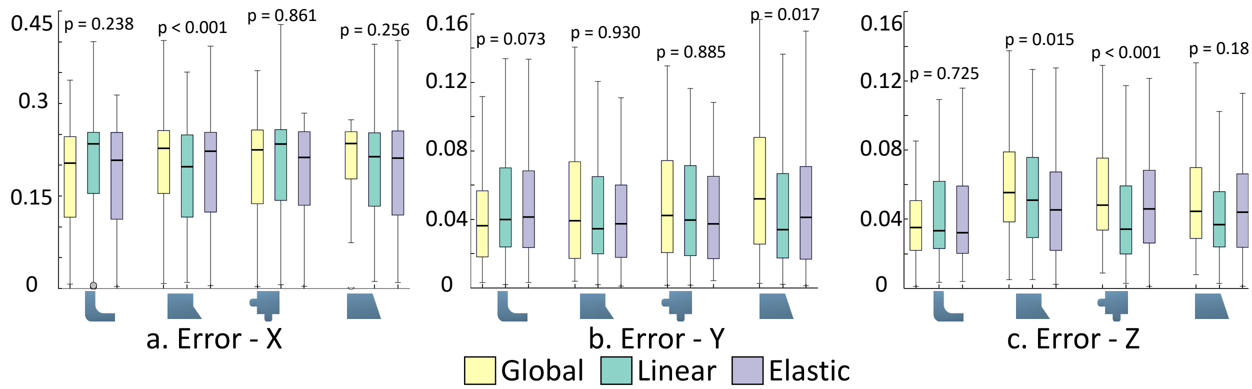


Figure 4.13: **Alignment Error** along (a) x-axis, (b) y-axis, and (c) z-axis across Jay, Shoe, Puzzle and Trapezium shapes using kinesthetic variants of Global, Linear and Elastic rotation techniques (Reprinted with permission from [225]).

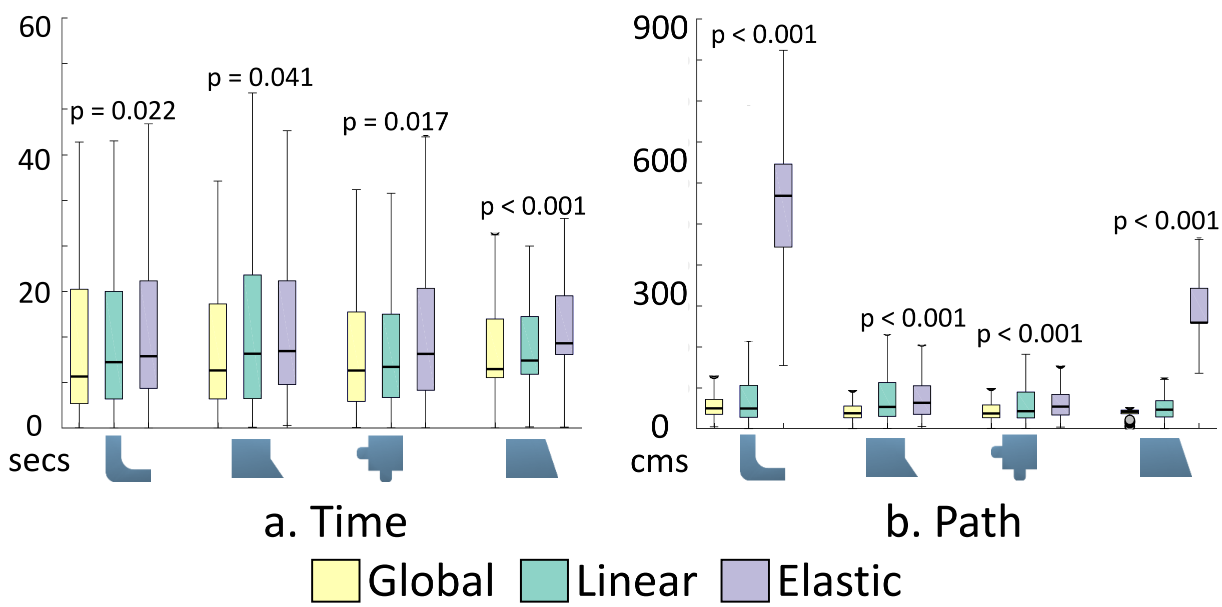


Figure 4.14: (a) **Completion Time**, and (b) **Stylus Path Length** across Jay, Shoe, Puzzle and Trapezium shapes using kinesthetic variants of Global, Linear and Elastic rotation techniques (Reprinted with permission from [225]).

4.5.5 Comparison of Rotation Techniques

4.5.5.1 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.

4.5.5.1.1 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. 4.13) for misalignment errors along each axis are as follows:

x**-axis:** We observed statistical significance (Figure. 4.13(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. 4.13(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. 4.13(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.

4.5.5.1.2 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. 4.14(a)) across most shapes shapes with a p-value $<$ 0.05 (Jay: 0.022, Shoe: 0.041, Puzzle: 0.017, Trapezium $\leq$ 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.

4.5.5.1.3 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.
- **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. 4.14(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 $\leq$ 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.

4.5.6 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.

4.5.6.1 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 4.15(a)). On the other hand, despite receiving positive feedback for fine rotational movements, Elastic technique was rated to be most mentally

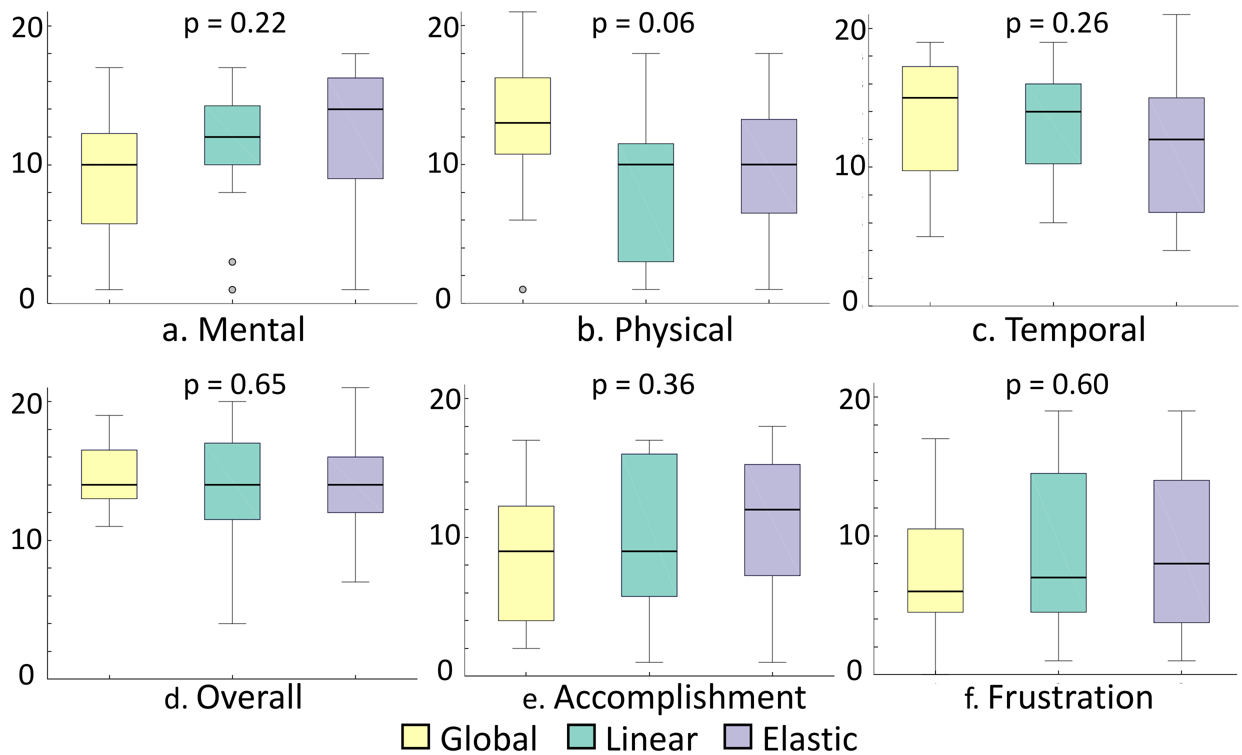


Figure 4.15: Statistical comparison for user ratings across rotation techniques using NASA Task Load Index [1:low; 21:high] (Reprinted with permission from [225]).

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. 4.15(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. 4.15(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. 4.15(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.

4.5.6.2 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 [232, 233] 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.

4.5.7 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.

4.5.8 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* [206, 207, 208] 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* [209, 210], 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.

4.6 Takeaway

4.6.1 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 [1, 17]. 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 [198] — 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.

4.6.2 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 [234]. 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.

4.6.3 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.

4.7 Conclusion

In this chapter, we systematically demonstrate how haptics, specifically force-feedback augments precise control for spatial object manipulation. We primarily explored spatial rotation as most works have explored translation and scaling based spatial tasks, with minimal exploration for rotational manipulation. Here, we designed and implemented three rotation metaphors complemented with perceptually coherent haptic feedback for precise spatial control. Our evaluation shares a fundamental insight on how force-feedback not only enables fine manipulation of virtual objects, in fact it facilitates a bio-mechanical support that minimizes mid-air fatigue, thereby increasing focus on the task performed.

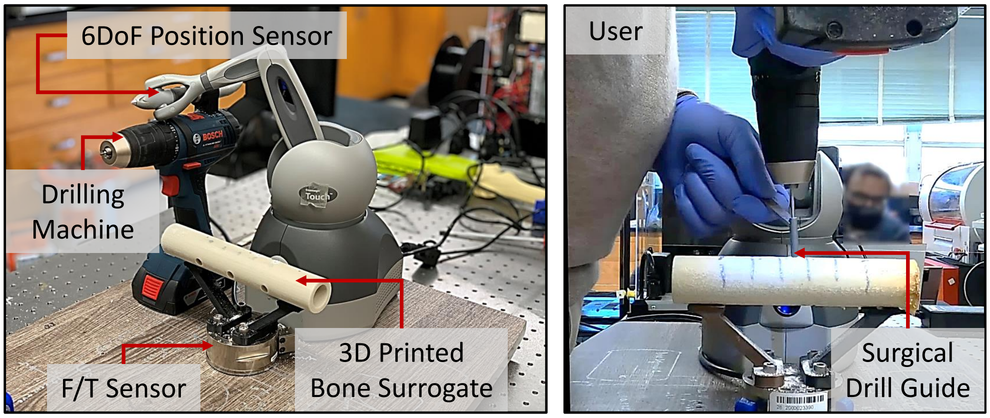
This chapter offers a glimpse of how kinesthetic feedback can afford an intuitive and perceptually familiar tangibility in spatial interactions. In our proposed metaphors, we investigate a wider spectrum of spatial control ranging from direct to indirect user control for object manipulation. These algorithms however are metaphorical in the sense that they draw from real-world experiences, but focused on interaction intuitiveness than emulating physical realism as is. This makes it difficult to measure and evaluate the motor strategies as most metrics are state based and seldom focus on the path themselves. In the following chapter, we deeply investigate a real-world precise tasks to observe and make sense of the physical affordances allowing fine motor control and hand-eye coordination. Also, investigate metrics to evaluate the physical precise tasks.

5. ORTHOPEDIC BONE-DRILLING ASSESSMENT THROUGH LAPLACIAN-BASED TRAJECTORY NOISE CHARACTERIZATION

5.1 Motivation

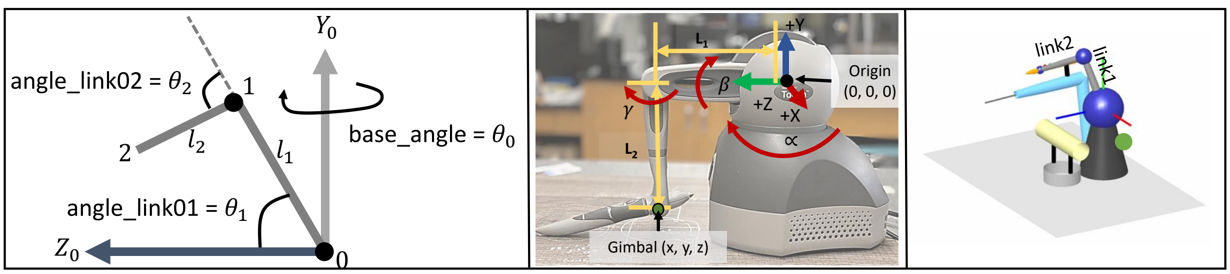
Precise motor control is a fundamental skill acquired through years of practice and experience. It furnishes the capability to perform skilled activities that require fine manipulation actions from the user. Tasks such as sculpting, manufacturing, and medical surgeries fall under this category, with the need for careful and precise hand motions in order to perform the high-precision tasks effectively. Orthopedic surgeries are one such set of high-precision tasks that necessitate the ability to make fine and careful motor movements while performing a surgical operation. The goal is to minimize any risk of damaging the bone, nerves, or tissues [144] during the surgery, thereby, ensuring patient safety. As a case in point, orthopedic surgery training and evaluation is critical, as well as, crucial for helping resident doctors build on their hand-eye coordination skills, and fine-motor perception skills. In this paper, our focus it to facilitate evaluative means for monitoring orthopedic resident training progress over the duration of their residency program.

From our interviews with expert surgeons, we learn that the evaluation of orthopedic resident training performance is not merely qualitative but completely *subjective*. The expert surgeon observes the residents visually and grades their performance based on that observation. Our main goal in this paper is to help improve orthopedic resident training by facilitating an objective, and preferably quantitative, means to evaluate training performance of orthopedic residents. For this, we designed a hardware setup to capture real-time bone-drilling data and developed a drilling signature to assess the quality of the drilling tasks. We demonstrate our evaluation approach by collecting data from an expert surgeon, computing the signature model of the expert, and subsequently evaluating the drilling performance of novice participants through a controlled lab experiment.



(a) Study Setup (b) Bone-Drilling Task

Figure 5.1: (a) We designed a hybrid (physical-digital) setup for bone drilling training using $3D$-printed bone surrogates simulating close-to-real bone properties; (b) Bone drilling task being performed on our setup using a surgical drill guide for better stability



(a) Schematic of the Kinematics Model (b) Kinematics Model Overlayed on the Position Sensing Device (c) Animated Representation using the Kinematics Models

Figure 5.2: Our forward kinematics model based on raw data provided by the position sensor, and computed the precise ($\sigma = 3$ mm) drill tip position.

5.2 Bone Drilling Data Collection

In order to propose our evaluation metric, it is important to standardize the training methodology in how bone-drilling training is currently conducted, as well as, the process of recording the drilling data. We discuss our setup and data collection approach in the subsequent sections.

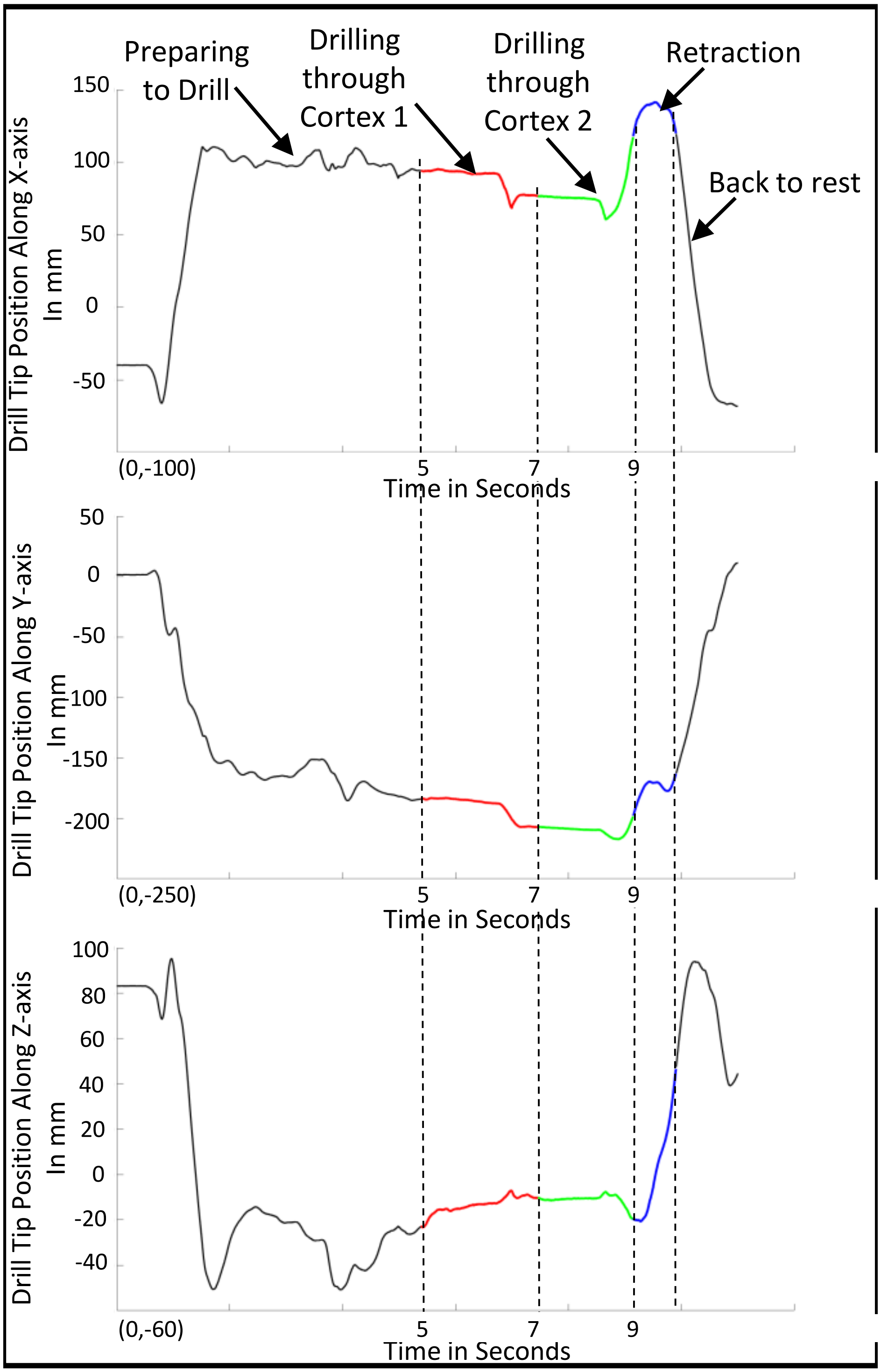


Figure 5.3: We manually identify and label different drilling phases for the drilling motion data inside the bone. Based on our kinematics model, we observe variants in positions along Y axis as it gradually moves away from the coordinate basis of the kinematics model; and closes in once outside the bone.

5.2.1 Physical Setup Design

The motivation behind designing a hybrid simulator (Figure. 5.1 (a)) was to develop a versatile device that provides the ability to utilize 3D printed customizable cortical bones for drilling and provides a detailed quantitative, as well as, visual feedback on the drilling performance. The physical set-up is focused on the 3D-printed bone-mimicking composite. The bone surrogate is manufactured using a special 3D-printable plaster employing the binder jetting technology [235, 236, 237]. 3D printing furnishes the ability to create complex geometries, and therefore, the testing sample is customized to the effect of being patient or bone-specific. In addition, the mechanical properties can be modified at the post-printing stage with an epoxy treatment. This treatment can produce various grades of hardness and toughness to simulate bones at different ages or conditions. In this work, two hardness grades were used, which replicated young (healthy) bone and osteoporotic bone. The bone simulants while being a work in progress, were design and developed on consultation with expert surgeons and their perception of an as-close-as-possible bone hardness owing to years of drilling experience. Therefore, the young bone's hardness was designed to be Shore 95D while that of an osteoporotic bone was Shore 45D.

The bone surrogate was clamped to a 6-dof ATI gamma force sensor (ATI Industrial Automation, USA), which helped record the drilling force and torque along all three coordinate axes. Further, a 1700 rpm Bosch hand drill (Bosch, USA) was connected to a Geomagic Touch (3D Systems, USA) 6DoF haptic device, which rendered only the position and orientation along all three coordinate axes as well. We did not render any haptic feedback with the device as the bone simulant takes care of it. Robust and stable construction followed by ease of using the setup while drilling were incorporated as the primary design criteria of the hybrid bone-drilling simulator.

5.2.2 Data Recording and Processing

Bone drilling and fracture fixation require high motor precision and drill-tip alignment accuracy in drilling through an exact location on the bone. Therefore, the 6DoF haptics device acted as a position sensor to record drilling motion data at the drill tip. This was achieved using a forward kinematics model (Figure. 5.2) specifically designed for an accurate representation of drilling trajectory. Owing to separate APIs (C++ and LabView), the haptic device and F/T sensor data were synchronized during the post-processing by matching time stamps from both sensor logs. Data synchronization also aided in segmenting the drilling region from the entire spatial trajectory which included spatial movements outside the bone; before and after the bone was drilled. We achieved this by corresponding the time series plots with the time stamps from the physical recording of the actual drilling task.

5.2.3 Evaluation Methodology

Drawing from literature review and interview with expert surgeons. more emphasis is be given to motion parameters (feed rate, drilling speed, and plunging distance) as they directly affect temperature rise and overall drilling performance. In order to evaluate a particular drilling performance, we initially studied each of the recorded bone-drilling parameters individually. A custom MATLAB function library was developed to extract these individual parameters from raw data, and compute few derived parameters as well. However, to form generalized conclusions, as well as, differentiate between expert and novice users, an extensive set of data may be required. Though manual analysis may have its benefits, it is time-consuming and tedious for larger data sets. On analyzing the motion data (Figure. 5.3) qualitatively, we observe increase in drill-tip distance along the Y-axis of the the kinematics model coordinate system; which we further analyze in deep as a part of our drilling performance assessment between novice and expert surgeons.

5.3 Technical Approach: Drilling Signature

Our goal is to characterize a given drilling trajectory with a signature in order to facilitate experienced surgeons with means to assess the training progress of the resident surgeons over the duration of their residency. Surgical bone drilling is a highly constrained and precise task meaning that the $3D$ trajectory of the drill is more or less straight going through the bone cortices and coming out. In such a scenario, it stands to reason that getting a measurable difference between the drilling trajectory of two individuals would be inherently challenging. Our preliminary findings indicated that $3D$ position of points in the operator's trajectory, net force, and drilling speed are insufficient metrics to draw a clear distinction between a novice user and an expert user in terms of drilling performance. One of the primary reasons that attributes to this limitation is the constrained nature of the bone-drilling activity. As a case in point, the drill tip is surrounded by the bone-material for the entire drilling duration except for the hollow cavity between two bone cortices in a *to-and-fro* motion — the user enters and leaves the bone from the same position. Consequently, the trends for the aforementioned metrics across the novice user groups look similar when compared to an expert surgeon thereby making it difficult to draw comparisons for any type of performance assessment of the drilling activity. In this work, we introduce a curve signature metric that we call the **drilling signature**. The main idea for the drilling signature is to help evaluate a resident's drilling task by comparing their trajectory to a gold standard; which is an expert surgeon for orthopedics training.

5.3.1 Rationale behind Drilling Signature

The design of our drilling signature is based on our observations of the difference between how expert and novice individuals control the drill. After several years of practice, expert surgeons insert the drill into the first cortex at a relatively high speed, move in reasonably slowly to the second cortex and pay attention to plunging once they pass through the second cortex (so as not to damage the soft tissue). On the other hand, novices begin cautiously right from the very beginning and therefore end up losing control at the end of the first cortex itself. This difference in expert and novice behavior has two implications on the geometry of the drilling trajectory. First, even though the nominal paths are "*straight*" (both going in and coming out), they are not sampled equally with time. In fact, from our experience, novice trajectories are generally densely sampled because they tend to maintain a slower speed in hope of getting better control. The second and more important observation is that the effect of noise generated through the drill's vibration, the bone's interaction with the drill, and the manual response are difference between experts and novices. It is these two observations — the sampling rate and the noise profile along the drilling trajectory — that inform the design a method to objectively (and preferably quantitatively) distinguish between novices and experts.

To characterize the sampling rate and noise profile along the drilling trajectories for a given operator, we draw from signal processing. There are many previous works noise characterization for applications such as fault analysis of electrical and mechanical components [238, 239, 240], cognitive neuroscience [241], biological spectral analysis [242], and image processing [243]. More recently, Cheyrev et al. [244] explain the use of path signatures as well as their use in machine learning. Additionally, signature-based machine learning models have also been used for distinguishing bipolar disorder and borderline personality disorder [245]. Similarly, Kormilitzin et al. [246] approach signatures from the point of pattern recognition in the CEQUEL clinical trial for diagnosing bipolar disorders. An alternate application is the use of the path signatures to predict a diagnosis of Alzheimer's disease [247]. However, with our current focus on $3D$ drilling trajectory, we borrow from prior works using the Laplace-Beltrami operator to conduct $3D$ shape analysis [248, 249, 250, 251, 252].

5.3.2 Conceptual Framework

In our approach to characterize the noise and sampling rate in the drilling trajectory, we build upon the known algorithm of Laplacian smoothing; which is a well known technique [253] that has been used extensively in computer graphics for curve and surface smoothing [254]. The basic idea is simple — for a given manifold (a curve or a surface) discretized in a piece-wise linear fashion (for curve this means a poly-line, for surface it is a polygonal mesh), we replace each vertex of the manifold with the weighted average of its neighbors. In the continuous case, this is essentially the application of the Laplace equation ($\nabla^2 f = 0$) for a harmonic function (f) defined on the manifold.

From a signal processing perspective, what Laplacian smoothing achieves is that it enforces the function f to become harmonic over a period of time thereby allowing it to reach it's steady state. In fact, the same principle is applied in heat diffusion problems. Now, applying the Laplace operator directly on the coordinates of a poly-line, which is essentially how our trajectories are represented, effectively diffuses the curvature on the trajectory. Another interpretation of the operator is that an eigen-decomposition of this operator is equivalent to removing high frequency noise in the manifold [255, 256, 257]. The equivalence between noise removal and diffusion to steady state provides a powerful clue toward developing a signature for our application.

We begin by first observing that for any poly-line approximating a given curve, a repetitive application of the Laplacian smoothing will ultimately lead to a completely straight line with uniformly sampled points. However, each point on the poly-line will take a different amount of time to reach the steady state. For instance, points whose neighborhoods are already straight (low-curvature and less noisy) will take less time to reach steady state than those that are noisy or highly irregularly sampled on the curve. Now we also note that the time for a given point to reach steady state can simply be described by the number of iterations it takes for this point to become static (i.e. there is negligible difference in the location of this point between two consecutive applications of smoothing).

Based on these observations, our idea for the drilling signature is rather simple. We repetitively apply Laplacian smoothing to the trajectory and record the number of iterations it takes for each point to reach steady state. Steady state is defined as a state where the euclidean norm a point before and after smoothing at a given iteration falls below a certain threshold. Once recorded, the number of iterations for each point is normalized and referred as the signature score (s) for a point on a given curve. For a curve P with k points on it, there will be ($\mathbf{S} = (s_1, s_2, ..., s_{k-1}, s_k)$) signature scores. This signature essentially characterizes the noise, curvature, as well as, sampling distribution in the drilling trajectory as we originally desired (Figure. 5.4).

5.3.3 Algorithm

For a given smoothing iteration i, let us consider a trajectory curve $P_i = (\mathbf{p_i^1}, \mathbf{p_i^2}, \mathbf{p_i^3}, \ldots, \mathbf{p_i^{k-1}}, \mathbf{p_i^k})$, where $p_i^j \in R^n$. The smoothed coordinate for every j^{th} point in P_i is given as:

$$\mathbf{p}_i^j = 0.5 \times (\mathbf{p}_{i-1}^{j-1} + \mathbf{p}_{i+1}^{j+1}) \tag{5.1}$$

The smoothing is applied successively to the smoothed iterations of the original trajectory P_0 until:

$$\|\mathbf{p}_i^j - \mathbf{p}_{i-1}^j\| < m \in R \tag{5.2}$$

Here, m is the threshold for euclidean norm between corresponding points of two consecutive smoothed trajectory curves to reach steady state. We found $m = 0.005$ as a suitable threshold to verify the steady state of the drilling trajectories recorded in our data collection. We compute the signature for each point on a given curve as the normalized number of iterations to reach steady state; discussed as follows:

$$s_j = \frac{s_k - s_{min}}{s_{max} - s_{min}} \forall j \in [1, k] \tag{5.3}$$

Here, $s_k \in$ [0,1] and S_{max} and S_{min} are the maximum and minimum signature scores along the entire drilling curve.

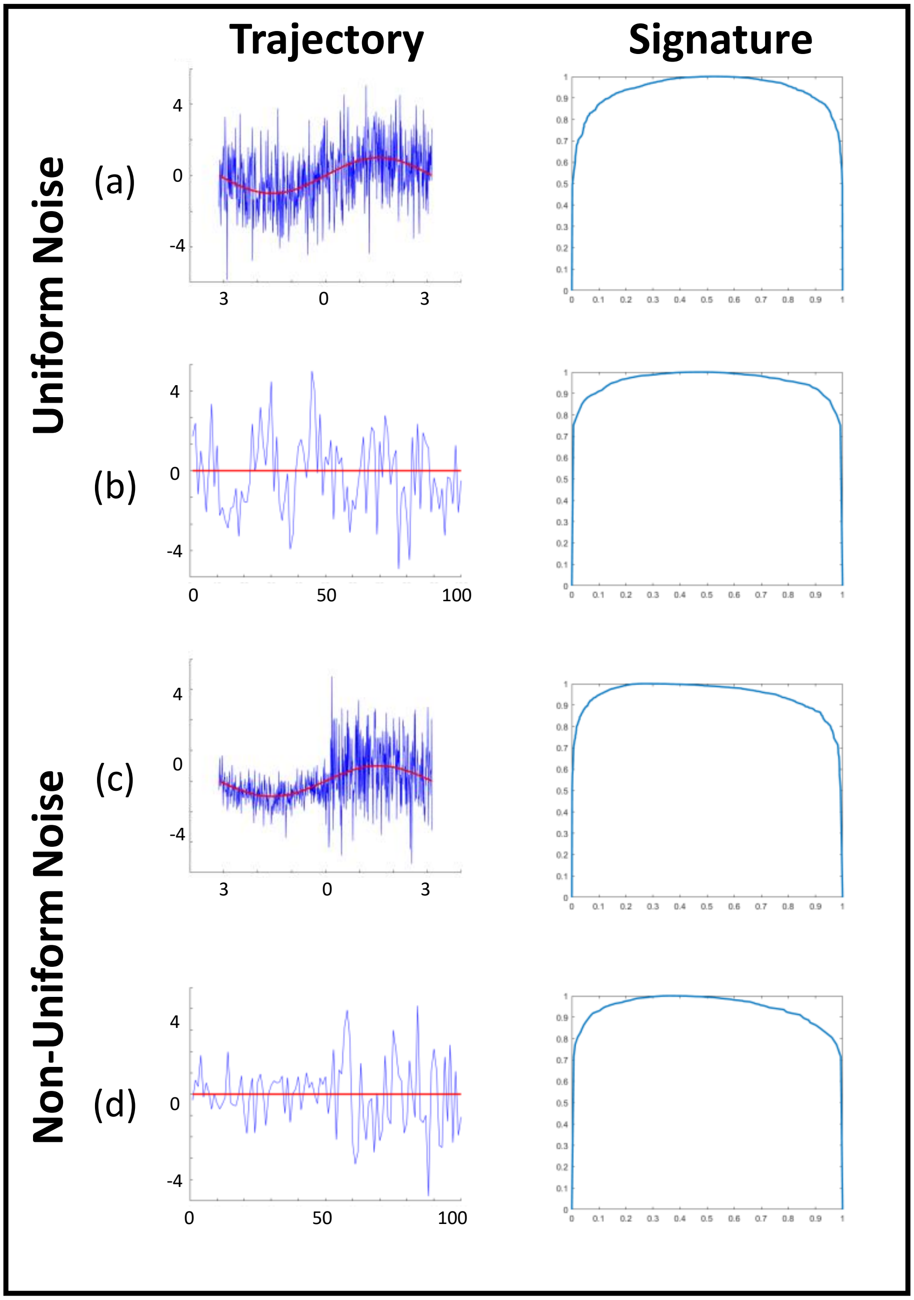


Figure 5.4: We demonstrate our conceptual framework for the drilling signature across two trajectories — **sinusoidal curve** and a **straight line** with uniformly and non-uniformly sampled noise. We observe an almost symmetric signature curve for the uniformly sampled noise profiles, whereas the signature is skewed to the right for the non-uniformly sample noise profiles across two different trajectories

5.4 Experiment

We evaluate our metric through preliminary bone-drilling experiments as discussed in subsequent sections.

5.4.1 Participants

Our interviews with expert orthopedic surgeons not only helped us understand current evaluation practices, but also, identify the level of resident expertise at each stage of the residency program beginning with the first year. We learnt that most first year resident surgeons get admitted with minimal or no prior experience with any type of bone-drilling tasks. Therefore, it is safe to assume that the bone-drilling expertise held by any first year resident is akin to that of a novice or any non-medical student who also hasn't had the opportunity to conduct a bone-drilling task. Owing to the simplistic nature of our bone-drilling setup, we assume that the learning curve would be same across the novices.

One of the key challenges of evaluating the signature metric is recruiting first year resident surgeons, who have a busy schedule, given the nature of their residency program. Therefore, under the assumption that novices possess minimal to no prior bone-drilling experience, we recruited 10 participants randomly sampled from undergraduate and graduate engineering students recruited through university advertisement*. The participants were within the age group of 18 to 30 years old. According to the information collected from the participants through a pre-study questionnaire, 8 participants had prior experience with manufacturing related drilling and 7 rated the expertise from an amateur to intermediate. Only one participant rated themselves as an expert in drilling from the point of engineering processes.

While the 10 participants served as novice users for our bone-drilling experiments, we also recruited an expert user, who has been an orthopedic surgeon for over 30 years. The expert surgeon is responsible for training orthopedic residents in bone drilling in the Department of Orthopedic Surgery at the UT Health Science Center in Houston, Texas. Our goal is

*Due to the challenges presented by COVID-19, it was difficult to visit any medical center to collect data.

to use the expert surgeon's signature as a gold standard to evaluate the performance for the novice users. Most expert surgeons are on active medical duty and it is difficult to schedule an appointment in advance to collect drilling data, which makes our gold standard an ongoing process of adding more expert as an when the opportunity arises to gather more expert drilling data.

5.4.2 Evaluation Tasks

Our evaluation srudy is a simple bone-drilling task using the $3D$-printed bone surrogates and high precision tools for recording the drilling data. We designed the setup and the drilling task with three goals in mind: (a) first, we wanted to evaluate the efficacy of our setup in terms of bone material, and the data recording hardware with the goal of standardizing the setup for orthopedics training, (b) second, we wanted to create a database of labelled drilling data that allows easy segmentation of position, force, speed, and other derived metrics for better analysis of a drilling task, (c) finally, we wanted to take a preliminary step towards objectifying the existing subjective and qualitative bone-drilling evaluation metrics, towards the possibility of quantifying drilling parameters in near future.

5.4.3 Procedure

The experiment involved drilling through a $3D$-printed bone surrogate for two bone variants of varying hardness; emulating healthy and osteoporotic bones mechanically and perceptually. The study took approximately 30 minutes per participant with a minimum duration of 30 minutes between two consecutive participants. The participants were asked to take care of minimizing the plunging distance during the practice as well as actual study trials. After every experiment, the drilling setup was sanitized, also, the drill bit was ensured to be free of bone-surrogate debris from prior experiments.The study started with the participants filling up a demographic questionnaire and answering pre-screening questions inquiring their prior experience with drilling. The participants were then given a general introduction to the experimental setup and brief demonstration of the bone-drilling task was also shown.

The participants and study investigators maintained a minimum distance of 6 feet during the study trials, masks worn by both parties at all times, also, there was a glass divider separating both. They were also given the option of donning a latex glove for health and safety reasons.

Practice: The participants began by getting themselves acquainted with the drilling simulator setup from two perspectives. First, if they are donning a glove, does it allow them to perform the drilling task comfortably and with minimum distraction. Second, if the height of the setup is ergonomically feasible for a less constrained drilling activity. We tackled the latter by providing a platform to the participants ensuring the setup is around the waist level for them, towards enabling a comfortable drilling experience. They were asked to practice drilling using a drill guide on either bone variants as randomized by the study investigator to minimize learning bias. The practice sessions lasted for about 4 - 5 minutes as most participants had prior exposure to handling a drilling machine.

Study Trials: The participants were asked to drill 10 holes across both bone variants i.e. 5 per bone. The order in which the bones were presented to the participants was chosen randomized and they completed drilling 5 for a given bone variant before moving on to the next bone. We asked the participants to start the drilling process only when the drill bit was touching the top surface of the bone. The participants were then given a signal to start the task, after which they picked up the drilling machine, inserted the drill bit through the drilling guide and started drilling the hole. Once they had completed drilling the hole, they were asked to retract the drilling machine and keep it back on the work-desk, marking the end of the trial. They were provided with a wet wipe to clear any bone debris stuck in the flutes of the drill bit. The participants were given a short break (30-60s) after each trial, and a longer break (approx. 3 minutes) after the first 5 trials while the study investigator installed the second bone on to the setup.

The same procedure was followed to collect data from the expert orthopedic surgeon as well.

However, the expert conducted 10 drilling trials for a given bone variant.

Data: For each of the trials performed by the participants, we recorded the raw event log containing the (a) 3D position data of the drilling machine, (b) time taken to drill, (c) force, and (d) torque data for a given trial.

5.4.4 Expert Signature and Drilling Quality Metric

We compute signature scores s_j ($, j \in [1, k]$) on each vertex $\mathbf{p^j}$ of the drilling trajectory, and use it as our primary metric to evaluate drilling performance of orthopedic resident surgeons. The normalized signature scores per trial for the expert orthopedic surgeon are plotted with respect to the normalized arc length of the particular trial trajectory. Subsequently, we plot the signature ($\mathbf{S}$) vs. normalized arc length (L) for all expert trials for a given bone type and further compute an *average curve* for all plots. Following this, we uniformly re-sample the signature along the arc length. Finally, we compute the *average curve* (Figure. 5.5) for a collection of drilling signatures for multiple trials of the expert. We treat this average curve for each bone type as the expert model (gold standard) for the drilling performance assessment.

5.4.4.1 Drilling Quality Metric:

We use the expert signature model to compute root mean squared error (RMSE) between the model curve and a given user trial signature curve. This value is what we define as the drilling quality metric. For a signature of a given individual (U), the re-sampled signature is given by $S^U = (s_1^U, s_2^U, s_3^U, ..., s_{j-1}^U, s_j^U),\ j \in [1, k]$. We compute the RMSE with reference to the experts model M as follows:

$$RMSE = \sqrt{\frac{\sum_{j=1}^{k}(s_j^E - s_j^U)^2}{k}} \tag{5.4}$$

Here, $S^E = (s_1^E, s_2^E, s_3^E, ..., s_{j-1}^E, s_j^E),\ j \in [1, k]$ is the expert signature model computed using the averaging method.

5.5 Results

We discuss the results of our experiments from the point of evaluating the drilling performances for novice users with respect to expert surgeons. In the subsequent sections, we conduct a quantitative assessment using the drilling signature metric with the expert surgeon as our drilling performance benchmark.

5.5.1 Expert Models for Drilling

In order to standardize the expert surgeon data as our reference measure, we compute two expert models (one per bone variant) using drilling signatures across all expert trials. We hypothesized that expert drilling performance would be consistent irrespective of the bone variant. However, we observed a difference in expert drilling signature scores between the osteoporotic and healthy bone types, and therefore, decided to benchmark each bone variant with an expert model specific to a bone based on the aforementioned approach (§5.4.4). For computing the model signature curve, we first re-sampled 2000 equidistant values along the X-axis of the drilling signature plot; that represents the normalized arc length. The purpose for this larger distribution was to evenly capture the drilling signature across all expert trials for a bone variant. Further, we compute the drilling signature values for each expert trial for a bone variant at the re-sampled arc length values using piecewise linear approximation. Subsequently, we calculate the average of the new drilling signatures computed at the resampled points, across all the trials for a given bone variant, thus, resulting in two expert drilling signature models across the two bone variants (Figure. 5.5). We use these two individual expert models as our benchmark reference to objectively assess the quality and consistency of an user's drilling trials across both bones.

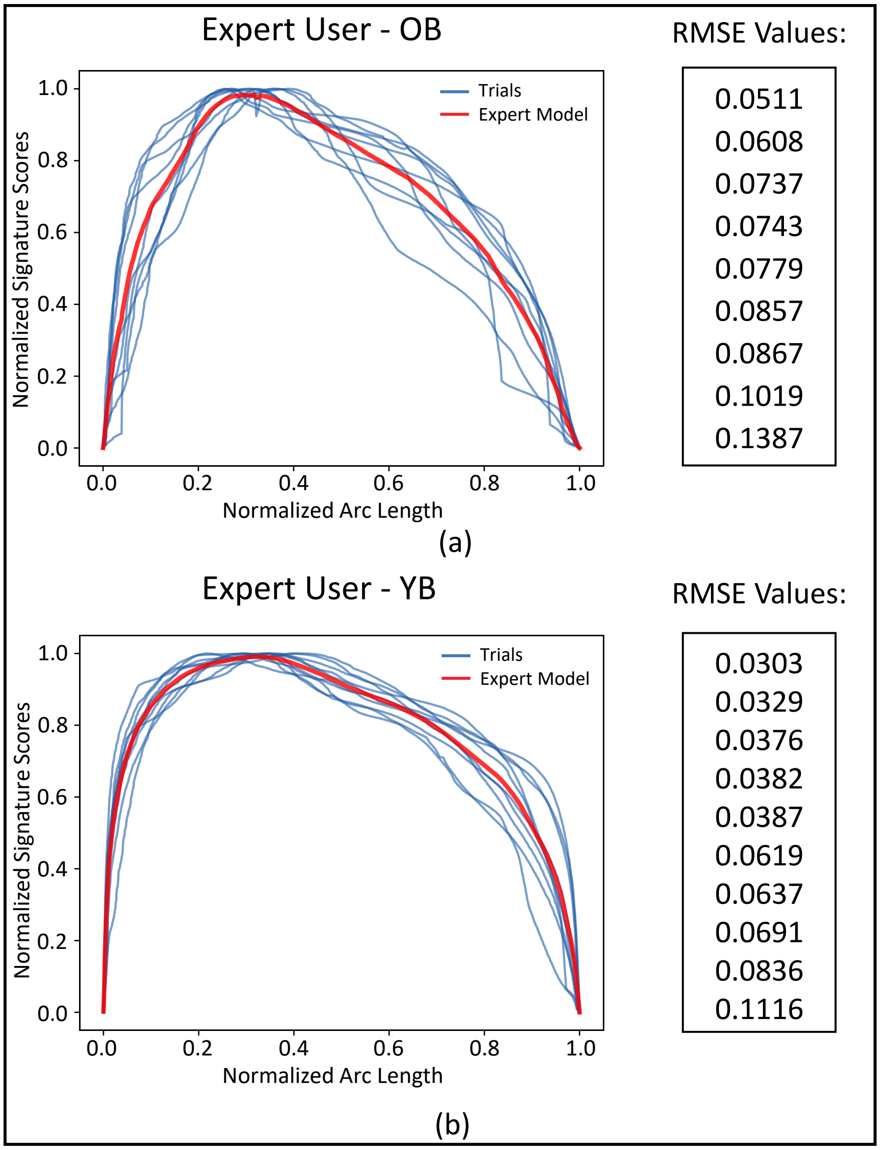


Figure 5.5: Plots showing the Signature Curves and Expert Model Curve (in red) for the Orthopedic Surgeon's trials on (a) Osteoporotic Bone (OB) and (b) Young Bone (YB), along with the RMSE Errors for each trial in comparison with respective expert model curves. The X-axis for the plots correspond to the Normalized Arc Length and the Y-axis corresponds to the Normalized Signature Scores.

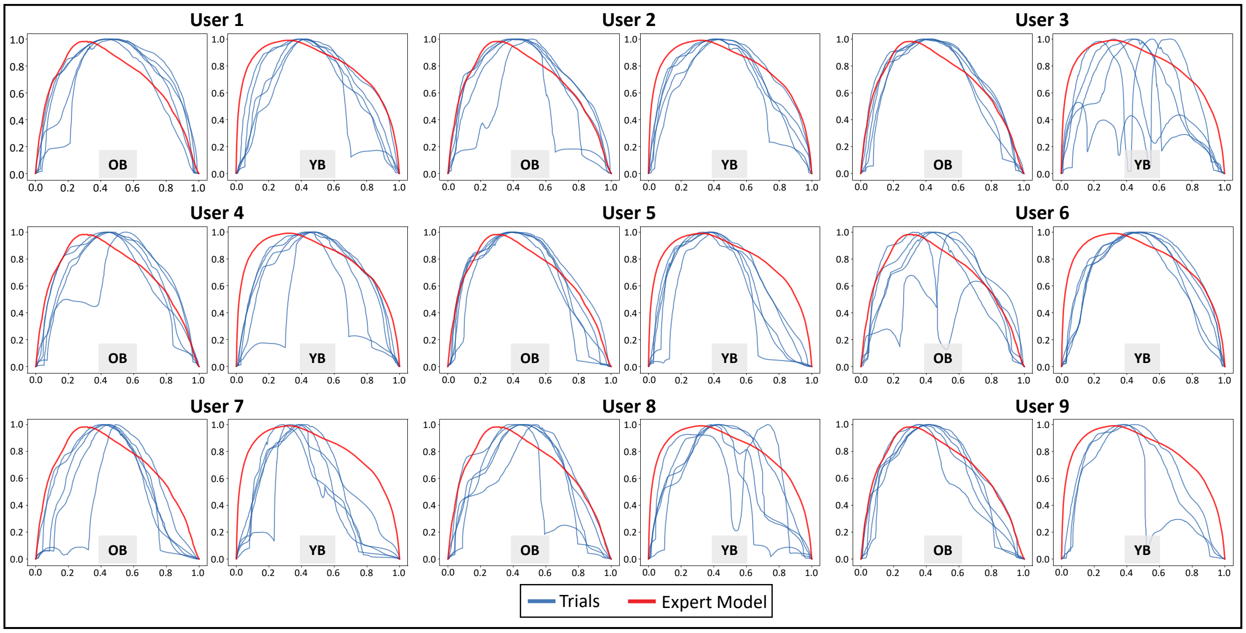


Figure 5.6: Plots showing the Signature Curves of all the 10 user trials across both the bones: Osteoporotic Bone (OB), Young Bone (YB) compared with the bone specific Expert Models. The X-axis for the plots correspond to the Normalized Arc Length and the Y-axis corresponds to the Normalized Signature Scores.

5.5.2 Quality of Performance

Our primary goal for creating the expert models was to come up with a benchmark that helps evaluate the drilling performance of the novice users for each bone variant. We followed the aforementioned approach (§5.4.4) of calculating the RMSE between the expert model for the specific bone type and each of the user trials' signature curve, which we refer to as the *quality of performance*.

We observed that our study participants in general performed worse than the expert surgeon across both bone variants. While we expected this due to the novice nature of their bone-drilling expertise, the overall quality of performance of users on the Young Bone (Avg. RMSE = 0.248) was worse than that of their performance on the Osteoporotic Bone (Avg. RMSE = 0.153). This is in contrast to the expert's performance on the two bone variants, where the expert performed better on the Young Bone (Avg. RMSE = 0.056) compared to the Osteoporotic Bone (Avg. RMSE = 0.075). A reason for this could be the difference in hardness levels of the bone variants, as the Young Bones are harder compared to the Osteoporotic Bone and provide relatively more resistance while drilling through the former bone simulant. This observation is also resounded in our comparison for each of the users signature plots across the two bone variants (Table 5.1), and it is clear that every user performed better, and was consistent in their performance while drilling through the Osteoporotic Bone variant.

We made some key observations on further analyzing the trends in user signature curves with reference to the expert signature models (Figure. 5.6. First, the expert models reached their peak signature values at smaller values of the normalized arc length than all of the users trials. This indicates a consistent as well as less noisy drilling trajectory for the expert surgeon. However, for the novice user signature plots, we observed the peak shifting towards the right side for all signature plots irrespective of the bone variant. One of the probable reasons for this shift in peak could be due to the users drilling being careful and deliberate while drilling the bone than the expert. This makes them go at a relatively slower pace and lose control once through the first cortex, as we observe in the peak shifting towards the later part of the normalized arc length. On the other hand, the expert surgeon completed their drilling trials much quicker than most novice users. Their approach to the different regions of the bones was also quicker, which can be explained by the steep initial slope of the expert models when compared to the gradual slope of the users' signature curves. Most users performed better on the Osteoporotic bone with respect to the initial steepness of the slope, which can again be explained by the resistance provided by the relatively harder Young bone variant.

5.5.3 Consistency of Performance

We define consistency as the repeatability of a user's drilling behaviour across consecutive trials for a given bone type, as well as, across both bone variants. On analyzing the user trials keep the expert model as our gold standard, we observe poor, but consistent drilling behavior for the Osteoporotic Bone variant (Figure. 5.6). On the other hand, the drilling behaviour for the Young Bone variant was poor as well as highly inconsistent as observed for the varying RMSE scores across drilling trials for all participants (Table. 5.1). This indicates that the study participants learned to adapt to the hardness of Osteoporotic bone relatively early and were comfortable drilling through it, whereas, they struggled with the drilling resistance experienced for the Young Bone variant.

We also observed that a higher consistency across one bone might not necessarily mean the user is experienced. This can be clearly seen for *User* 3 (*User* 3 YB plot in Figure. 5.6), whose RMSE for the Osteoporotic Bone was the lowest of all the users, but second highest for the Young Bone. We observe the opposite behavior for *User* 6, whose consistency across trials was better for the Young Bone (range of RMSE = 0.09), when compared with the trials on Osteoporotic Bone (range of RMSE = 0.22). The expert on the other hand, consistently performed better across both the bone types (range of RMSE for Young Bone = 0.081; Osteoporotic Bone = 0.087).

5.5.4 Participant Specific Observations

While we observe the general trends in quality and consistency of performance for the users in the above sections, there are some interesting things to note about some of the specific signature curves of the users. Firstly, almost all users have at least one trial, where the signature curves dip and then rise again to form a second peak (See trials from *User* 3 *YB, User* 4 *OB, User* 6 *OB, User* 7 *YB, User* 8 *OB/YB and User* 9 *YB* in Figure. 5.6). This dip is usually observed towards the middle and later half of the signature curve, also, the lower signature score in that phase signifies less iterations required to reach a steady state for the drilling trajectory, which might be caused by the users stopping their drilling motion for a small amount of time, before proceeding through the remaining regions of the bones. This is better explained by the sudden rise and forming of the second peak, which shows the continuation of the drilling action. Another interesting observation is the sudden change

Osteoporotic Bone						Average
User 1	0.11	0.13	0.16	0.17	0.27	**0.17**
User 2	0.06	0.08	0.13	0.24	0.30	**0.16**
User 3	0.07	0.08	0.11	0.13	0.14	**0.11**
User 4	0.11	0.11	0.15	0.16	0.28	**0.16**
User 5	0.09	0.11	0.13	0.14	0.19	**0.13**
User 6	0.10	0.15	0.16	0.24	0.32	**0.19**
User 7	0.17	0.20	0.24	0.27	0.44	**0.26**
User 8	0.14	0.15	0.22	0.22	0.28	**0.20**
User 9	0.09	0.14	0.15	0.17	0.18	**0.15**
Young Bone						**Average**
User 1	0.10	0.21	0.23	0.26	0.37	**0.23**
User 2	0.11	0.16	0.18	0.23	0.23	**0.18**
User 3	0.30	0.30	0.32	0.35	0.44	**0.34**
User 4	0.15	0.16	0.27	0.29	0.42	**0.26**
User 5	0.20	0.30	0.31	0.32	0.37	**0.30**
User 6	0.16	0.20	0.22	0.22	0.25	**0.21**
User 7	0.35	0.38	0.38	0.39	0.40	**0.38**
User 8	0.27	0.27	0.27	0.28	0.38	**0.29**
User 9	0.19	0.28	0.40	N/A	N/A	**0.29**

Table 5.1: RMS Error Values for each of the users' trials for both bone variants, when compared to the bone specific Expert Models

in the slope of the signature curves for some of the participants (See trials from *User* 1 *OB, User* 2 *OB/YB, User* 4 *YB, User* 5 *OB/YB, User* 7 *OB/YB, User 9 OB* in Figure. 5.6). These sudden changes in the slopes are usually seen in the initial and final sections of the curves and may correspond to a sudden change in the drilling action by the user. The flatter slopes signify very small changes in the signature scores, which may be due to a slow and gradual drilling motion by the novice user. On the other hand, steeper slopes signify a big change in the signature score, which may be a result of an abrupt change in drilling strategy as the user proceeds with the drill bit inside the bone surrogate. This is also indicative of the apprehension expressed by novice users while drilling through the first cortex as well as second in order to minimize the plunging distance.

5.6 Takeaway

In this section, we highlight some key limitations of our work and discuss the findings.

5.6.1 Limitations

Our drilling signature successfully helps distinguish between the overall bone-drilling behaviour of a non-expert user, with respect to an expert surgeon. However, one of the fundamental limitations of our metric is the lack of a ground truth reference to evaluate the efficacy of our metric. In this paper, we benchmark the drilling performance of an expert surgeon as our reference comparison, although, the presence of a ground truth would have helped form a fundamental basis towards the development of novel user performance metrics. Furthermore, we only had one expert surgeon as our user performance benchmark. This limitation is brought by the varying level of expertise across orthopedic surgeons, also, how many years of bone-drilling experience is sufficient to help compute our expert model. Recruiting more expert surgeons would be one of our immediate future goals to strengthen our evaluation assessment. On similar lines, there is a need to collect more user trials from novice users, as well as, resident surgeons across different years of training. This will not only help us understand the distinction between a novice (first year resident) and expert user, also, compare training progress with orthopedic residents in their second and later years of residency.

We also experienced long drilling signature computation times (approx 15 - 20 minutes) for a given user trial. One of the primary reasons for this is the relatively longer drilling duration of the novice users, therefore, resulting in larger trajectory points ($> 10,000$). This limitation can also be attributed to our threshold parameter m that ensures a steady state for a given drilling trajectory, which is by far the most optimal approach for computing the signature until a considerable steady state has reached. Therefore, there is a need for efficiently recording user drilling data i.e. minimizing irrelevant trajectory points recorded outside the bone, as well as, an optimal threshold parameter to speed up the signature computation process. In addition to the signature plots, we observed the histogram plots for the drilling signature also to show distinctive distributions for different user expertise and bone variant. One of our near goals is to explore the histogram plots of novice users and compare its efficacy with respect to the expert model histogram.

5.6.2 Multi-modal Data

We record and process different types of data such as the drilling force, drill tip position, and drilling speed for a bone-drilling activity. While the focus of this work primarily emanates from the drilling trajectory, our preliminary analysis of other parameters have shown observable differences in the force and speed profiles of expert and novice users. We believe that an individual's drilling behaviour is not only dependent on their physical motion, but also, in the way they apply force while drilling, as well as, the rate at which they drill through a solid object based on the material resistance; which in our context is a $3D$-printed bone surrogate. Since force and speed data emulate signals across a time duration, we could extend our signature approach to characterize drilling behaviour based on data other than the drilling trajectory. The collective analysis of different physical parameters of bone drilling could help us better understand parameters such as force, which isn't as comprehensible as spatial motion or drilling speed.

5.6.3 Bone Materials

In this paper, we conducted our user evaluation based on two bone variants — *Young* and *Osteoporotic*, emulating perceptual and physical properties of bones across young and old age groups respectively. $3D$-printing the bone surrogates makes it easier to design, manufacture, and improvise upon the material properties. Similar to our metric, the current bone models are experimental and constantly improved based on expert surgeon feedback to match the material properties of an actual bone. Our comparison of novice vs. expert users shows inconsistent and erratic signature plots for the Young Bone variant trials. We believe that user performance was affected by material hardness of the Young Bone surrogate, and designing a bone with varying intermediate hardness between the Young and Osteoporotic bone hardness could provide a new way to train orthopedic residents. The idea is to observe, analyze, and understand if novice users learn to drill from softer to harder bones or the opposite way, so as to develop fine motor control crucial for patient safety in orthopedic surgery.

5.7 Conclusion

In this chapter, we present how the general area of precise motor control is under-explored, not only in the virtual, but also, in the physical world. We conduct our exploration through the example of orthopedic training surgery owing to its high demand for skills in fine-motor perception, careful hand-eye coordination and bi-manual motor control towards conducting safer orthopedic surgeries. Our main contribution here is establishing a framework in designing physical setups for enabling such tasks, also, recording the spatial data for visual and statistical analysis in evaluating user performance. To note, current evaluative practices for precise actions are qualitative and mainly based on the objectivity of the person evaluating. Therefore, one of the key challenges faced by us was to find or develop a metric that evaluates user drilling performance, moreover, how resident surgeons perform compared to expert surgeons.

The stepping stone in investigating precise control lies finding relevant works, guidelines, instructions and knowledge that can further our research. However, the under-explored nature of this area demanded for a fundamental and deeper investigation on understanding *Where*, *When*, and *How* in $3D$ space, precise actions are afforded. There is a rich space from the point of proxemics, kinesthetics and analytics that requires further exploration to enable, measure and evaluate precise actions for highly skilled tasks in the future.

6. SUMMARY OF CONTRIBUTIONS

In this chapter, we summarize our contributions in enabling, measuring, and evaluating precise motor control in spatial interactions from the three key perspectives of proxemics, kinesthetics, and analytics.

6.1 Proxemics

We began by identifying some key knowledge gaps in existing SUIs which limits the affordability to perform fine motor actions in an intuitive and perceptually familiar manner. In order to bridge these gaps, we make the following contributions

– We design a novel SUI called the Clock-Maker's Work-Space configured to allow precise actions being performed close to the body (akin to the physical world) using high-precision motion tracking.

– We further systematically evaluate the CMWS with traditional MR systems, where interactions happen at an arm's length; and find that that similar to the physical world, proximity to actions in the virtual environment affords precise control as well.

– We confirm this through a systematic comparison with the physical counterpart of the precise spatial task, and observe similarities in motor strategies across both (virtual and physical) interfaces for spatial object manipulation.

Our findings from this work form a fundamental basis on how future AR/VR/MR interfaces should be designed to afford intuitive interaction experiences for performing fine and gross motor tasks.

6.2 Kinesthetics

We further narrow our scope on conducting a deeper investigation of a single manipulation action, specifically spatial rotation and how we can augment it using haptic-feedback. To facilitate this

- We designed three rotation algorithms drawing from different physical experiences in order to afford coarse and precise spatial rotation of virtual objects.
- We complement the rotation algorithms with perceptually coherent haptic feedback, specifically force-feedback for an enhanced sensorimotor perception towards precise spatial rotation actions.
- On conducting a systematic evaluation of the haptic assisted rotation algorithms with their non-haptic counterparts, we found that not only haptic feedback provided a rich and intuitive spatial manipulation experience; it also helped mitigate fatigue as experienced in prolonged usage of existing spatial interfaces.

Therefore, haptic (and kinesthetic) perception are important in facilitating fine-motor perception for performing precise spatial tasks, and its a rich space that needs further exploration for performing spatial tasks that are not possible in the physical world.

6.3 Analytics

The first two approaches were fundamental to how space and perception afford precise motor control in spatial interfaces. However, precise spatial tasks have often been evaluated from the lens of state based variables (time, error,.etc) and for us to actually measure and evaluate precise motor strategies in these tasks, there are little to no metrics that study the motion of the task being performed. To better understand this, investigate precise physical tasks, specifically, orthopedic surgery training.

- We begin by designing a hybrid (physical-virtual) training simulator that integrates $3D$ printed bone-surrogates designed to provide a physical and perceptual familiarity to an actual bone while drilling, also, digital sensors (position, force, torque) to record user action and response to the bone while performing the bone-drilling task.

– We further establish a systematic data collection and analysis pipeline for easy recording and evaluation of training performance parameters of resident surgeons.

– We also develop a novel metric based on Laplacian noise characterization to compute signature from drilling trajectories. The signature represents the noise, curvature, and point distribution of the user trajectory and is used to compare performance with respect to a gold standard (expert surgeons in our case). The signature metric can also be used to evaluate training progress across different years of orthopedic residency.

By analyzing a real world precise task, we come to the understanding that fine motor actions involve complexity and nuances that is under explored by existing research. It further necessitates the need to study precise tasks and come up with metrics to evaluate the fine motor strategies towards performing the task.

6.4 Long-Term Vision

The main focus of this PhD dissertation has been working towards problems that provide a fundamental insight on how precise motor control can be afforded in existing spatial interfaces. In fact, our explorations through proxemics, kinesthetics, and analytics help lay the groundwork for future avenues in manifesting perceptually coherent action-perception experiences. We discuss some prospects as follows:

– From the ***proxemics*** point of view, spatial interfaces could be designed to afford proximal interaction in order to support highly skilled activities such as sketching, sculpting, and similar task requiring fine motor dexterity.

– This could also lead to further investigation on designing guidelines for SUIs that afford a variety of such tasks or a single task, but with a feature rich interaction environment.

– While these avenues encourage new research, at the same time, technological advancements needs to happen especially for motion tracking hardware. Existing systems are focused on medium to large tracking environments where the focus is on arm or shoulder level movements. However, fine actions happen at finger and wrist level which is currently under-supported and could benefit form robust close space tracking technologies in near future.

- From the point of ***haptics***, the aforementioned skilled tasks could benefit from perceptually coherent sensory perception towards intuitive interaction experiences, which we hypothesize will support these fine motor tasks in virtual interfaces
- Additionally, general guidelines could be drawn for haptic-affordance and bio-mechanical stability for a series of spatial task or a specific activity requiring fine-motor perception.
- While close spaces afford precise actions, providing haptics at finger (cutaneous) or wrist level feedback would further improve the visuo-motor coordination necessary for performing precise spatial tasks.
- And finally from the scope of *analytics*, we could identify parameters in addition to user trajectory to characterize precise control in precise physical tasks.
- Also, design performance metrics that could be interchangeably used to measure and evaluate precise actions in the physical and virtual world.

We hope that this work is many of such journeys towards leveraging innate human abilities for designing an intuitive and perceptually familiar spatial interaction experience.

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