TwinSpin: A Virtual Ball in a VR Controller Enabling In-Hand 3DoF Rotation

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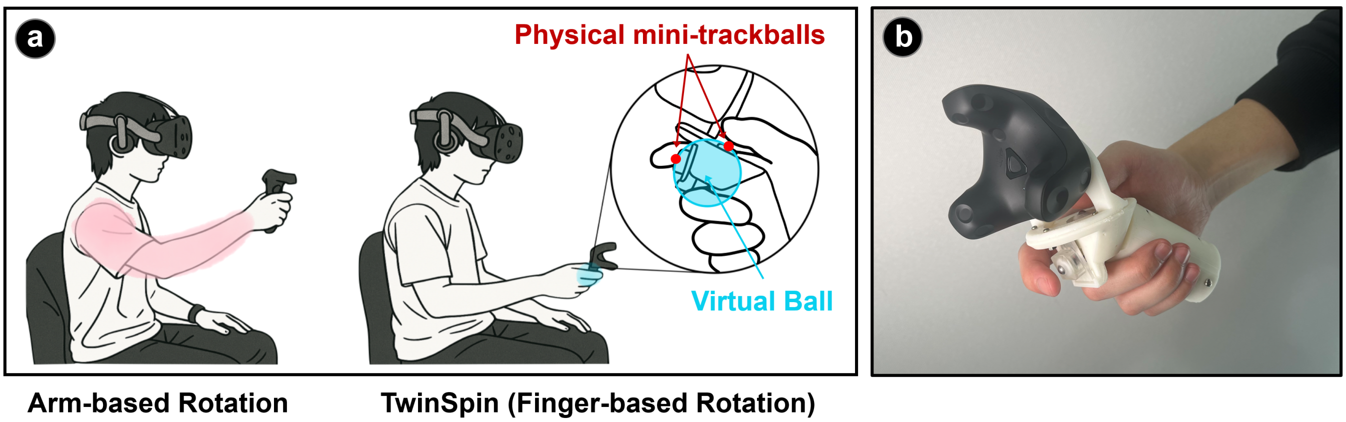

Figure 1: TwinSpin enables in-hand 3DoF rotation through finger movements in a VR controller. (a) Illustration comparing conventional arm-based rotation technique with TwinSpin during VR object manipulation. TwinSpin employs two physical mini-trackballs, manipulated by the thumb and index finger, based on the intuitive metaphor of rolling a virtual ball in-hand. (b) The proof-of-concept TwinSpin prototype.

Abstract

In-hand rotation is a natural motor skill of humans, yet current VR controllers mainly rely on arm and wrist movements to rotate virtual objects, leading to significant arm motion and fatigue. To address this, we propose TwinSpin, a VR controller employing two embedded mini-trackballs manipulated by the thumb and index finger. Its design is based on the intuitive metaphor of rolling a virtual ball in-hand to achieve three degrees-of-freedom (3DoF) rotation, leveraging finger dexterity to reduce arm movement and improve task efficiency in VR object manipulation tasks. Through docking tasks in both direct and distant object manipulations, our evaluation showed that TwinSpin significantly reduced arm travel distance, arm rotation, and task completion time compared to conventional arm-based rotation techniques. In line with the objective metrics, participants reported lower perceived physical demand, effort, and less perceived fatigue in the wrist, arm, and shoulder. We also share deeper analyses of the parallel control of translation and rotation, as well as optimal rotation trajectories, to gain further insights into user behavior with TwinSpin. To the best of our knowledge, this is the first attempt to enable full in-hand 3DoF rotation in a power-grip style VR controller.

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CCS Concepts

• **Human-centered computing → Interaction techniques**; **Virtual reality**.

Keywords

3D manipulation, interaction design, virtual reality

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1 Introduction

Human hands are naturally capable of highly dexterous finger movements [22, 43, 57], such as rotating objects in-hand—for example, spinning knobs or assembling puzzle pieces. However, current consumer practice in VR controllers primarily rely on a "wrist-arm rotation" mechanism, where users rotate virtual objects by rotating their wrists and arms. This approach necessitates considerable engagement of large muscle units, potentially causing physical strain. Furthermore, due to joint mobility constraints, users often need to reposition their wrist and arm repeatedly (i.e., perform clutching gestures [57]) to derive various orientation. These issues may be resolved if VR controllers allow users to leverage their in-hand rotation ability; e.g., "roll" objects with their fingers rather than swing their arms.

In this context, researchers have explored in-hand rotations utilizing finger dexterity. Froehlich et al. [13] introduced the GlobeFish and GlobeMouse, desktop input devices featuring six degrees of freedom, enabling users to perform rotations by rolling a trackball with their fingers in 3D graphics applications. Similarly, Kim et al. [28, 29] showed that in-hand rolling with a spherical VR input device outperforms standard VR controllers in manipulation tasks. Nonetheless, integrating such finger control into mainstream power-grip VR controllers (e.g., Meta, Pico, VIVE), where users wrap their fingers securely around a handle, remains challenging without conflicting with the existing input space of VR controllers.

In this work, we present TwinSpin, a VR controller that enables in-hand three degrees-of-freedom (3DoF) rotation using a virtual ball metaphor—mimicking the motion of rolling a ball in-hand—through two small embedded trackballs with thumb and index finger control (Figure 1). Finger movements on these trackballs map to corresponding 3D rotations of a virtual ball. To our knowledge, this is the first attempt to design a VR controller with a power-grip form factor that enables users to perform in-hand 3DoF rotation, preserving most of the existing input space and form factor.

In the evaluation, we compared the amount of arm movement (translation and rotation), perceived task load and fatigue, and time performance of TwinSpin with baseline methods (Wrist-Arm Rotation and HOMER [5]) through docking tasks involving direct object manipulation (Study 1) and distant object manipulation (Study 2). Furthermore, we conducted translation–rotation parallel control and optimal rotation analyses for each scenario to deeply understand users' object manipulation skills with TwinSpin.

Our main contributions are summarized as follows:

(1) We introduce TwinSpin, a VR controller enabling in-hand 3DoF rotation through finger movements on two embedded trackballs, using a virtual ball metaphor within a power-grip form factor.
(2) Experimental evaluation of TwinSpin's benefits in terms of task time, the amount of arm movement (wrist, forearm, elbow, upper arm, and shoulder), lowered perceived task load (physical demand and effort), decreased perceived fatigue in the wrist, arm, and shoulder, compared to the baselines.
(3) In-depth analyses of users' skill differences between TwinSpin and the baselines; e.g., enhanced parallel coordination of translation and rotation due to better division of labor between fingers (for rotation) and an arm (for translation).

2 Related Work

We briefly review three key areas: how existing input devices have considered finger dexterity, how it has been leveraged in 3D object manipulation, and foundational studies on integral and parallel control in object manipulation.

2.1 Finger Dexterity Considerations in Input Device Design

The homunculus model from neurophysiology illustrates that smaller muscle groups, such as fingers and hands, occupy disproportionately more area in the somatosensory and motor cortices compared to larger muscle groups like the wrist, elbow, and shoulder. This suggests that smaller muscle groups could provide advantages in performing dexterous tasks. Early studies have empirically compared the control performance of various limb segments and have shown through Fitts's Law studies that fingers offer higher bandwidth than other body parts [31, 42]. Leveraging these data, Card et al. [7] conducted calculations and predicted that finger-based input could outperform traditional mouse interfaces. Zhai et al. [57] further validated this empirically, showing that their FingerBall, a ball-shaped 6DoF input device utilizing finger dexterity, significantly reduced task completion times compared to glove-based input methods without finger-level operation. Based on these results, they suggested that future designers should consider utilizing the fingers for input operations when designing input devices.

However, contrasting results from Gibbs et al. [17] and Hammerton et al. [18] showed that the hand (activated by the wrist) could outperform the thumb in certain target acquisition tasks. Although these studies did not include fingers other than the thumb, Balakrishnan et al. [2] observed similar results using a point-select task, where isolated use of the index finger alone demonstrated lower bandwidth than wrist or forearm movements. However, they found significantly better performance when combining thumb and index finger in a pinch grip. Therefore, they emphasized that instead of simply incorporating fingers, it is important to design input devices that strategically utilize each limb segment based on its strengths. This aligns with Zhai et al.'s argument [57] that optimal dexterity arises from appropriately assigning roles to both small and large muscle groups, rather than relying on a single segment for the entire operation.

Therefore, TwinSpin was designed to enhance performance in rotation tasks—traditionally handled by large muscle groups such as the wrist and arm—by utilizing the smaller muscle groups such as the fingers. Instead of simply assigning the entire rotation task to a single finger, it introduced a virtual ball metaphor that engages both the thumb and index finger, reflecting the motor skills used for in-hand rotation in the real world.

2.2 Leveraging Finger Dexterity for 3D Object Manipulation

Previous research has explored spherical controllers that leverage finger dexterity to facilitate object manipulation tasks [12, 29, 44]. Froehlich et al. [13] proposed a desktop input device for graphics applications that supports 6DoF tasks. For rotation, they utilized a trackball capable of freely rotating in all directions. Extending spherical controllers to immersive environments, Kim et al. [28] introduced a pressure-sensitive ball-shaped VR controller and validated its effectiveness in 7DoF object manipulation tasks compared to conventional controllers. Englmeier et al. [12] also evaluated a tangible handheld sphere for AR object manipulation tasks. In addition to spherical controllers, various alternative form factors have been proposed. For example, the Roly-Poly Mouse [39] supports both 2D and 3D interactions by rolling its hemispherical base along a surface, and Thumble [34] is a thumb-worn wearable device that enables users to rotate virtual objects through subtle movements by rolling a trackball beneath the thumb using the index finger. Despite these innovations, most commercial VR controllers maintain a power-grip form factor, and spherical or other alternative designs have not yet fully replicated functionalities offered by traditional controllers, such as multiple buttons. Furthermore, spherical controllers are more likely to be accidentally dropped because they lack a firm handle like those in power-grip designs.

Meanwhile, efforts have emerged to incorporate finger dexterity within power-grip VR controllers to enhance rotation capabilities. TORC [33] is a rigid haptic VR controller that provides haptic feedback to convey properties of virtual objects, such as compliance and texture. The researchers also proposed an interaction scenario where users manipulate objects by moving their thumb on TORC's 2D trackpad. They conducted a two-level docking task to evaluate the interaction; however, the rotation stage was limited to 1DoF rotation. Similarly, Kim et al. [27] used the touchpad of a commercial VIVE controller, operated with the thumb, to rotate objects using the Arcball [45] and Two-axis Valuator [1] methods. This approach, similar to TORC, relies exclusively on the thumb within a 2D input surface, without involving other fingers. It also does not support direct control of 3DoF rotations, such as pitch, yaw, and roll. Meanwhile, Hinckley et al. [22] demonstrated that integrated 3DoF control using a 3D input device achieved faster performance compared to mouse-driven 2D input techniques such as the Virtual Sphere [9] and ArcBall [45]. These findings suggest the importance of supporting full 3DoF control in VR object manipulation. To the best of our knowledge, no prior work has explored the utilization of finger dexterity to enable 3DoF rotation within a power-grip style VR controller.

2.3 Integral and Parallel Control in Object Manipulation

Building upon prior foundational work, the design of input devices should be informed by the perceptual and motor characteristics of the tasks they are intended to support. Garner et al. [15, 16] characterized the perceptual structure of multidimensional visual objects by distinguishing between integral and separable. When attributes are perceptually combined into a unitary whole—such as the lightness and saturation of a color—they are considered to form an integral structure. In contrast, when attributes remain distinct—such as size and lightness—they are considered to form a separable structure. Building on Garner's work, Jacob et al. [24] argued for the importance of matching the perceptual structure of a task with the control structure of the input device, and confirmed through empirical studies that doing so can lead to better performance. For example, in an integral task involving the adjustment of a graphic object's location and size, they found that a three-dimensional tracker resulted in faster task performance compared to a 2DoF mouse with mode switching. Similar findings have been reported in other studies. Chen et al. [9] showed that, for a 3D rotation task, the virtual sphere technique—simulating a physical 3D trackball—yielded better performance than using sliders. Likewise, Hinckley et al. [22] found that their 3D Ball input device, which offers integrated control, enabled faster task completion than 2D input techniques.

However, subsequent research suggested that fully integrating all DoFs does not always lead to the best performance. Veit et al. [47] found that in a 3DoF orientation task, complete integration of all degrees of freedom was not always optimal. In follow-up work [48], they proposed an interaction technique that switches between integrating and decomposing DoFs depending on the phase of the task (i.e., ballistic vs. control) in a 3D positioning context. Wang et al. [50] also found that object transportation and orientation can be controlled in parallel. However, they observed that these processes do not overlap throughout the entire interaction. Extending Jacob's concept of integral and separable perceptual structures, Wang referred to this from a visuomotor control perspective as a parallel structure.

Interpreting TwinSpin's mechanism in light of these prior studies, we propose that TwinSpin provides conceptually integrated control for 6DoF object manipulation tasks. This design aligns the control structure of the input device with the perceptual structure of the task, as advocated by Jacob et al. [24]. At the same time, from Wang [50]'s perspective of motor control space, TwinSpin separates the coupled translation and rotation functions, which are typically handled together through arm-based input. It does so by assigning them to the arm and fingers, respectively, allowing for parallel interaction. In our study, we conducted an in-depth analysis to investigate how users reduce translation–rotation mismatches during interaction. We also examined whether users tend to follow an optimal path during rotation. Through these analyses, we aimed to observe and understand how finger-based interaction influences user behavior during object manipulation tasks.

3 TwinSpin

In this section, we introduce the core concept of TwinSpin, describe the key design decisions, and detail the hardware implementation of our prototype.

3.1 Concept

TwinSpin is inspired by the metaphor of rolling a ball in-hand. We simulate a single large virtual ball by placing two smaller physical balls beneath the thumb and index finger. This allows users to intuitively rotate virtual objects as if rolling a ball between their fingers while holding their VR controllers (Figure 1), and the virtual object's rotation follows the finger-driven rotation of the trackballs. This approach is expected to offload rotation tasks from the arm to the fingers, minimizing overall arm movement. Unlike traditional Wrist-Arm Rotation techniques, which rely on arm movements to control both the position and orientation of the virtual object, TwinSpin enables independent control—rotating objects with finger while translating them with arm. Therefore, TwinSpin is expected to allow simultaneous control of all 6 degrees-of-freedom through coordinated movements [56].

3.2 Design Decisions

3.2.1 Trackball. TwinSpin may be implemented using either physical trackballs or optical finger navigation sensors (e.g., PixArt PAW-A350). Between the two options, we chose physical trackballs

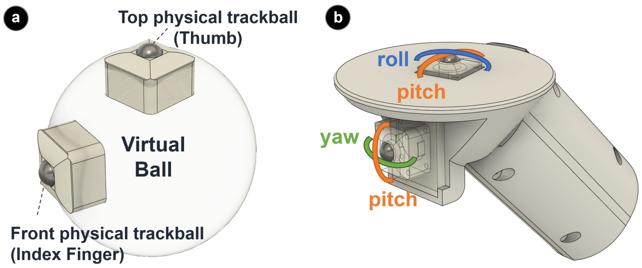


Figure 2: (a) Virtual ball metaphor. (b) Mapping of 3DoF rotations to each trackball.

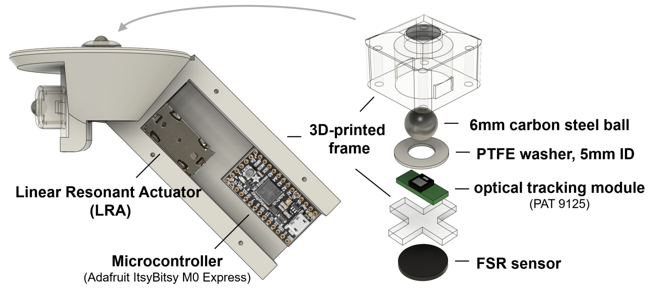


Figure 3: Hardware implementation of the TwinSpin prototype, showing the controller's internal structure (left) and the custom optical trackball sensor (right).

because it can deliver tangible rotary feedback during object rotation. We then considered different trackball sizes. The size of the trackballs common in trackball mice [40] would require considerable real estate on the controller and would result in a substantial revision of controller design. Accordingly, we intended to adopt trackballs whose size is smaller than that of the buttons (approximately 1 cm in diameter) found on commercial VR controllers (e.g., Meta and VIVE controllers).

3.2.2 Position of Trackball and Degrees of Freedom. According to Napier et al. [37], the inner three digits (thumb, index, and middle fingers) can perform supplementary roles when gripping a handle. Thus, we opted to use the thumb and index finger, already employed in conventional VR controllers for button and trigger operations. However, a small trackball is challenging for a single finger to manipulate across more than 2DoF (e.g., difficulty rotating the top trackball in the yaw direction, Figure 2). Therefore, two separate trackballs, each supporting 2DoF, together achieve full 3DoF manipulation.

3.2.3 Rotation Mapping. The two trackballs are mounted orthogonally to each other and aligned with the finger pads of the thumb and index finger, respectively. As a result, the thumb controls pitch and roll rotations, while the index finger manages pitch and yaw rotations (Figure 2b). This design aligns rotation directions with those experienced when rolling a ball with the fingers. Each trackball, however, is not limited to just two axes; it also allows for diagonal inputs, enabling rotations across multiple axes. For practical usability, we configured the rotation gain based on natural finger movement range. Human fingertips typically span 16–20 mm [10], meaning a 6mm trackball can rotate about one full turn per fingertip sweep. We established a gain where three trackball rotations correspond to one complete object rotation, optimizing the balance between subtle finger movements and effective rotation. Nevertheless, trackball gain preferences can vary individually, akin to mouse cursor sensitivity preferences.

3.2.4 Wrist Rotation for Fine Control. Considering the natural involvement of the wrist in real-world in-hand rotations, TwinSpin integrates wrist rotation, which controls object rotation with a one-to-one mapping, in addition to finger control. According to Gao et al. [14], static non-isomorphic rotations are the fastest during ballistic phases, while isomorphic rotations are the fastest during correction phases. Therefore, TwinSpin distinguishes between coarse finger control and fine wrist control, configuring trackball rotations primarily for large adjustments to reduce wrist rotation. TwinSpin also adopts a *Hand*-fixed coordinate system, which provides the most intuitive interactions when combined with wrist rotations.

3.2.5 Dual Functionality of Trackballs. Enabling the trackball to function as a **button** allows users seamless transitions between object selection and rotation without repositioning their fingers. Moreover, this dual functionality reduces the spatial cost of integrating trackballs into existing VR controller form factors by combining button and rotation functionalities.

3.3 Implementation

3.3.1 Optical Trackball Sensor. Off-the-shelf mini trackballs, which use hall effect sensors [35], has an insufficient angular resolution for smooth and fine control of a virtual ball. Therefore, we built custom trackballs with an optical trackball sensor. A 6 mm diameter carbon steel ball is supported by a 5 mm inner-diameter washer made of PTFE (Poly Tetra Fluoro Ethylene) to minimize rotational friction. An optical tracking module (PixArt PAT 9125 [23]) with a resolution of approximately 630 counts per revolution (on a 1.0 mm diameter surface at a 1.0 mm distance) is placed under the ball. A 3D-printed resin frame secures the ball in place, allowing it to rotate without slipping out. The carbon steel balls are rubbed with abrasive material to create a textured pattern on their surface, enhancing the detection of rotational motion by the optical sensors.

3.3.2 Controller Body. The controller body was 3D-printed in a form suitable for a power grip mimicking the commercial VR controllers (e.g., Meta and Pico). It equips a VIVE Tracker 3.0 on top for positional and rotational tracking in VR. Each trackball is connected to a microcontroller (Adafruit ItsyBitsy M0 Express) via I2C. The microcontroller reads delta x and delta y values from the two trackballs and transmits this data to a Unity program through serial communication. Moreover, each trackball is mounted on an FSR (Force Sensitive Resistor) that detects the pressure applied on the trackball. When the pressure exceeds a predefined threshold, a button event is triggered, and a built-in LRA (Linear Resonant Actuator) inside the controller vibrates, providing haptic feedback. This mechanism effectively simulates a trigger button, while allowing the trigger threshold to be programmable. Furthermore, using FSR sensors instead of mechanical buttons prevents unintended trackball movements that could result from height changes when pressing (a phenomenon similar to the Heisenberg effect [4, 53]).

4 Study 1: Direct Object Manipulation

Evaluating a given solution across targets located in diverse locations is important to verify its versatility [55]. In a survey of consumer VR applications, Maslych et al. [36] classified object locations in the *environment reference frame* as either *peripersonal* (within the user's arm reach) or *extrapersonal* (beyond arm reach). Therefore, as a first step, we conducted a comparative study against the baseline Wrist-Arm Rotation technique to evaluate TwinSpin's performance during direct object manipulation scenarios in VR.

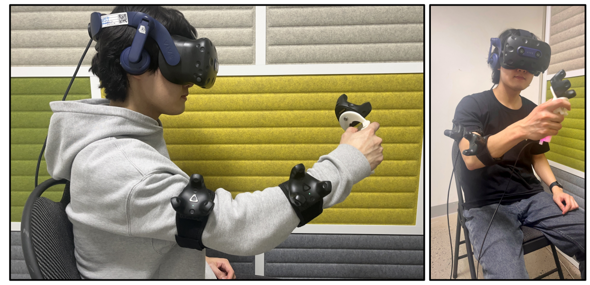


Figure 4: Experimental setup of Study 1 & 2, showing a participant performing the Docking Task in VR.

4.1 Study Design

The study was a within-subjects design with an independent variable of interaction technique, which had two levels: Wrist-Arm Rotation and TwinSpin. The order of the techniques was counterbalanced across participants. Each participant completed four training blocks and four testing blocks for each technique, with each block consisting of 20 task trials. The dependent variables are task completion time, total arm movement, perceived task load [20], and perceived fatigue [10].

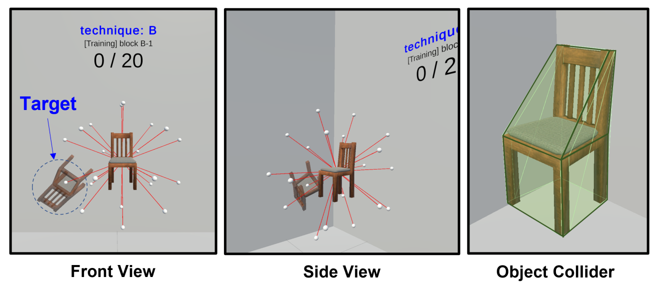


Figure 5: Docking task used in Study 1 (possible target positions (white spheres) and rotation axes (red lines) are shown in this figure for explanation).

4.2 Task

Rotation can occur not only when an object is fixed in place but also simultaneously with translation [25, 56]. Therefore, we designed a 6DoF Docking Task that incorporates selection, translation, and rotation, which have been commonly used in prior research [3]. The 3D chair object was chosen as the rotating object because, unlike a tetrahedron, it was a more familiar and less symmetrical object, making it easier to perceive unique orientations [49]. When the task started, participants rotated a virtual chair to match a given pose (Figure 5).

According to guidelines for evaluating object manipulation in VR [3], it is recommended that targets be distributed across all three spatial dimensions. To support this, we utilized an icosahedron to place targets uniformly in 3D space, covering a diverse set of movement directions and allowing for comprehensive evaluation across a range of positions and orientations. The icosahedron's centroid was positioned 45 cm in front of and 20 cm below the participant. Its circumradius was set to 20 cm. In each trial, the target object appeared randomly at the centroid of one of the 20 faces. A vector from the icosahedron's centroid to each face centroid defined 20 rotational axes, with the rotation angle set to 150 degrees. Similar to position, the rotational axis was randomly assigned in each trial. Each position and rotational axis was used exactly once across the 20 trials, resulting in 20 unique combinations of position and orientation sampled without replacement.

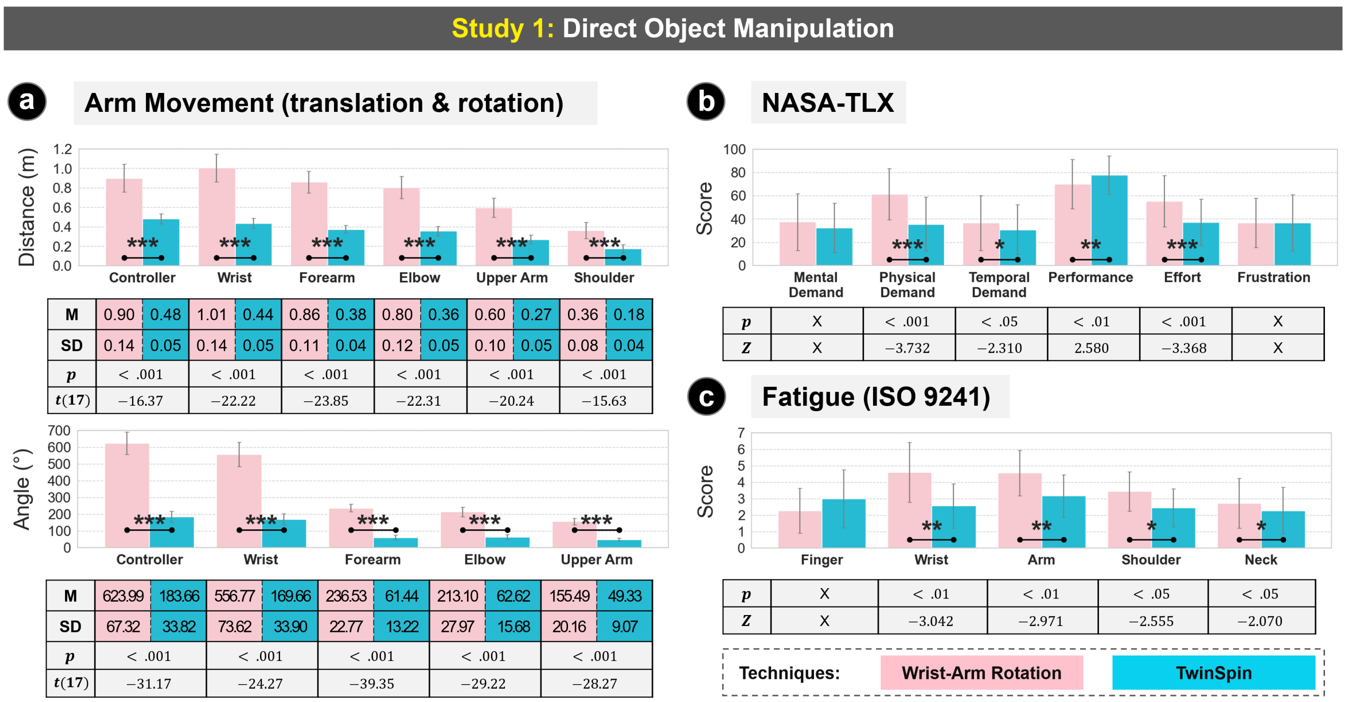
At the start of each trial, participants touched a button at a specific location with the cursor (a 1 cm-diameter sphere), which triggered the appearance of the problem and started arm movement logging. The size of the chair model was 7 cm × 7 cm × 14 cm, and alignment error thresholds were set to 0.01 m for position and 10 degrees for orientation [51]. When the participant moved the cursor over the object collider (Figure 5), the chair was highlighted with a white outline and became grabbable. Once the chair was correctly aligned, it turned green and provided audio feedback. The trial was completed only when the chair remained correctly aligned for 0.7 seconds [56]. After each trial, participants could rest their hands on their thighs and initiate the next trial at their own pace by touching the start button again.

4.3 Techniques

The Wrist-Arm Rotation is a widely used method in VR object manipulation. After moving the cursor to the chair and holding the button (grab state), participants can move and rotate the chair using their wrist and arm. During this process, they can utilize a clutching gesture by releasing and regrasping the object [57]. Participants can use the trackballs as a grip button with either their thumb or index finger, depending on their preference. In TwinSpin, when the user clicks the trackball to select an object, the object becomes attached to the cursor and can be rotated by rolling the trackball; clicking again releases the object.

4.4 Apparatus

Two techniques were implemented on the same hardware (Figure 3). The hardware was connected via a 1.1m USB cable for UART communication with the PC, which did not restrict the user's movement required for task performance. Participants wore a VIVE Pro 2 headset, and two VIVE trackers were placed at the center of the upper arm and forearm, respectively (Figure 4).



(a) Distance (m)

	Controller		Wrist		Forearm		Elbow		Upper Arm		Shoulder	
M	0.90	0.48	1.01	0.44	0.86	0.38	0.80	0.36	0.60	0.27	0.36	0.18
SD	0.14	0.05	0.14	0.05	0.11	0.04	0.12	0.05	0.10	0.05	0.08	0.04
p	$< .001$		$< .001$		$< .001$		$< .001$		$< .001$		$< .001$	
$t(17)$	−16.37		−22.22		−23.85		−22.31		−20.24		−15.63	

(a) Angle (°)

	Controller		Wrist		Forearm		Elbow		Upper Arm	
M	623.99	183.66	556.77	169.66	236.53	61.44	213.10	62.62	155.49	49.33
SD	67.32	33.82	73.62	33.90	22.77	13.22	27.97	15.68	20.16	9.07
p	$< .001$		$< .001$		$< .001$		$< .001$		$< .001$	
$t(17)$	−31.17		−24.27		−39.35		−29.22		−28.27	

(b) NASA-TLX

	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration
p	X	$< .001$	$< .05$	$< .01$	$< .001$	X
Z	X	−3.732	−2.310	2.580	−3.368	X

(c) Fatigue (ISO 9241)

	Finger	Wrist	Arm	Shoulder	Neck
p	X	$< .01$	$< .01$	$< .05$	$< .05$
Z	X	−3.042	−2.971	−2.555	−2.070

Figure 6: Results from Study 1. Error bars show standard deviations, and asterisks indicate statistically significant differences ($* : p < .05, ** : p < .01, *** : p < .001$). In the table, M = mean, SD = standard deviation, p = p-value (two-tailed). (a) Mean arm movement (translation and rotation), (b) Raw NASA-TLX scores, (c) Fatigue scores (ISO 9241).

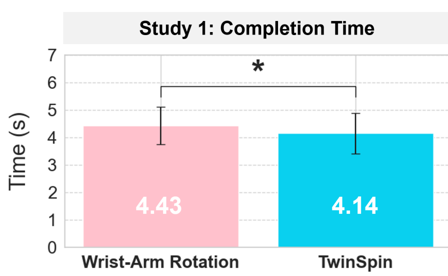


Figure 7: Mean completion time for each technique in Study 1. Error bars show standard deviations, and asterisks indicate significant differences (*: p < .05)

4.5 Arm Movement Measurement

We aimed to examine the movements of each arm segment in greater detail while using each technique. This would help us identify which part of the arm is most commonly used. We gathered translation and rotation data from three trackers placed on the Controller, Forearm, and Upper Arm. The relative rotation between each tracker was then calculated to assess the rotation of joints like the wrist and elbow. The participant's arm length was measured before the experiment to estimate the positions of the wrist, elbow, and shoulder.

4.6 Participants

18 participants were recruited from the university (6 women and 12 men, ages=18-33, M=22.65, SD=3.80). All participants were right-handed, and all but one had prior VR experience. Four participants used VR device once or twice per month. Each session lasted approximately 1.5 hours.

4.7 Procedure

First, participants signed the IRB (Institutional Review Board) consent form and received an explanation of the experiment. Next, participants wore motion trackers to record arm movements during interactions, and their arm length was measured. They then put on a VR headset and verify the estimated positions of the wrist and elbow. A 3-minute familiarization session was conducted to help participants understand the operation of Wrist-Arm Rotation and TwinSpin. Afterward, they completed four training blocks, followed by a 3-minute break, and then proceeded with four testing blocks. Break intervals were set at 2 seconds between trials and 1 minute between blocks. The participants were instructed to complete the task as quickly as possible. After the testing phase was completed, participants responded to the raw NASA-TLX questionnaire (RTLX) [6, 20] and assessed their fatigue levels for each body part via the ISO 9241 questionnaire [11].

4.8 Analysis

We collected a total of 2,880 data points (18 participants × 2 techniques × 4 blocks × 20 trials) from the testing blocks. Outliers were

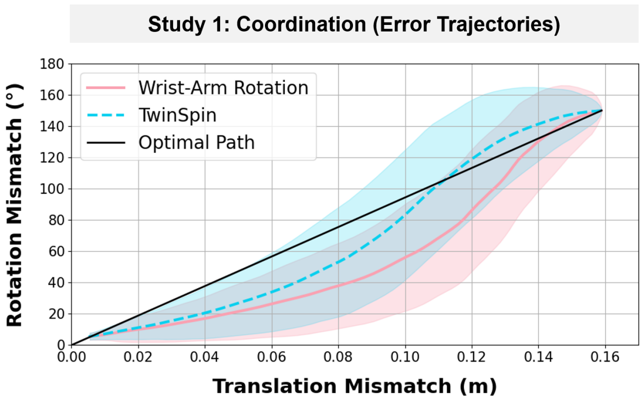


Figure 8: Average error trajectories in translation-rotation mismatch space for each technique in Study 1. Error bands show standard deviations.

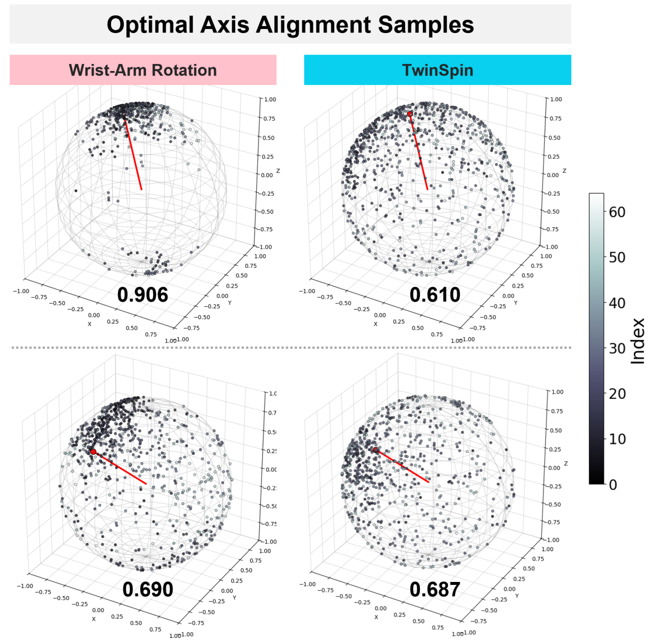


Figure 9: The first row shows the condition with the largest score difference between techniques (optimal axis: −0.58, 0.58, 0.58), and the second row shows the smallest difference (optimal axis: −0.93, 0.36, 0.00), based on data from all participants in Study 1. The markers were plotted on the unit sphere.

removed based on the completion time using Tukey's fences (1.5 × IQR). Both completion time and arm movement met the normality assumption (Shapiro-Wilk test, $p > .05$), allowing for a paired samples t-test to be conducted for each measure. For raw NASA-TLX [6, 20] and fatigue ratings [11] (measured on a 7-point scale), the Wilcoxon Signed-Rank test was used.

4.9 Results

4.9.1 Completion Time. The mean completion time (in seconds) for TwinSpin ($M = 4.14$, $SD = 0.68$) was **6.55%** faster than the mean time for Wrist-Arm Rotation ($M = 4.43$, $SD = 0.74$). This difference was statistically significant ($t(17) = -2.26$, $p < .05$ (two-tailed)), indicating that TwinSpin resulted in faster completion times compared to Wrist-Arm Rotation (Figure 7).

4.9.2 Arm Movement (Translation). The translation of arm movement (in meters) for TwinSpin was consistently lower than Wrist-Arm Rotation across all arm segments (wrist, forearm, elbow, upper arm, and shoulder). These differences were statistically significant for all segments ($p < .001$), indicating that TwinSpin reduced arm translation compared to Wrist-Arm Rotation (Figure 6a).

4.9.3 Arm Movement (Rotation). The rotation of arm movement (in degrees) for TwinSpin was consistently lower than Wrist-Arm Rotation across all arm segments (wrist, forearm, elbow, and upper arm). These differences were statistically significant for all segments ($p < .001$), indicating that TwinSpin reduced arm rotation compared to Wrist-Arm Rotation (Figure 6a).

4.9.4 Task Load. Compared to Wrist-Arm Rotation, TwinSpin significantly reduced perceived physical demand ($p < .001$), effort ($p < .001$), and temporal demand ($p < .05$), and increased self-rated performance ($p < .01$). However, no significant differences were observed in mental demand and frustration (Figure 6b).

4.9.5 Fatigue. Participants rated fatigue in the finger, wrist, arm, shoulder, and neck on a seven-point scale (low to high) based on the ISO 9241 questionnaire [11]. Compared to Wrist-Arm Rotation, TwinSpin significantly reduced perceived fatigue in the wrist ($p < .01$), arm ($p < .01$), shoulder ($p < .05$), and neck ($p < .05$). However, no significant difference was observed in finger fatigue (Figure 6c).

4.10 In-Depth Analysis

We conducted an in-depth analysis to gain a deeper understanding of user behaviors while using two different techniques. The following describes the metrics used in our analysis.

Coordination To compare how coordinated each technique was in reducing translation and rotation error [24, 58], we calculated the difference between the optimal and actual paths in the translation-rotation mismatch space during manipulation. The normalized RMSD (Root Mean Square Deviation) was used to measure how closely the movement followed the optimal path.

Average Rotation Amount The average rotation amount of the virtual object (i.e., chair) in each trial. The optimal value was 140 degrees (150 target degrees - 10 threshold degrees).

A rotation for an alignment task can be represented as a series of delta rotations. Therefore, to analyze rotation trajectories, we collected delta rotations (represented as quaternions) at intervals of 0.05 seconds. The collected quaternion data was then resampled using SLERP interpolation to normalize trial duration (80 samples for Study 1, 100 samples for Study 2). In Figure 9, each marker plotted on the unit sphere corresponds to one delta rotation sample. Because our analysis focuses on axis alignment, we only visualized the axes of delta rotations in an axis-angle representation. Marker brightness represents the temporal order of rotations (i.e., the sample index within each trial). Therefore, if rotations closely followed the optimal axis from the beginning, markers with lower indices would appear closer to the optimal axis. To exclude cases where the rotation axis changes multiple times during fine control in the correction phase [54], only the first 80% of the entire process (i.e., the ballistic phase [54]) was analyzed. Additionally, where the angle of delta rotation—i.e., the rotation magnitude around the delta rotation axis—was less than 10 degrees were also excluded.

Optimal Axis Alignment Score The absolute dot product was used to compare how closely the rotation was performed to the optimal rotation axis. Since this metric does not consider the rotation direction but instead focuses on proximity to the optimal rotation axis, the opposite axis receives the same score. The score ranges from 0 (orthogonal alignment) to 1 (perfect alignment).

4.10.1 Coordination. Since the normality assumption was violated (Shapiro-Wilk test, $p < .05$), the Wilcoxon Signed-Rank test was conducted. The normalized RMSD for TwinSpin ($M = 0.293$, $SD = 0.027$) showed an **10.67%** improvement over Wrist-Arm Rotation ($M = 0.328$, $SD = 0.062$). This difference was statistically significant ($Z = -2.199$, $p < .05$), indicating that TwinSpin resulted in more coordinated movement compared to Wrist-Arm Rotation (Figure 8).

4.10.2 Average Rotation Amount. Since the normality assumption was violated (Shapiro-Wilk test, $p < .05$), the Wilcoxon Signed-Rank test was conducted. The average rotation amount for TwinSpin ($M = 449.73$, $SD = 62.79$) was **30.26%** higher than Wrist-Arm Rotation ($M = 345.22$, $SD = 46.03$). This difference was statistically significant ($Z = 3.724$, $p < .001$), indicating that TwinSpin invovled more rotation during manipulation compared to Wrist-Arm Rotation (Figure 8).

4.10.3 Optimal Axis Alignment Score. Since the normality assumption was satisfied (Shapiro-Wilk test, $p > .05$), a paired samples t-test was conducted. The absolute dot product for TwinSpin ($M = 0.575$, $SD = 0.036$) was **13.14%** lower than the absolute dot product for Wrist-Arm Rotation ($M = 0.662$, $SD = 0.047$). This difference was statistically significant ($t(15) = -8.071$, $p < .001$), indicating that Wrist-Arm Rotation resulted in better alignment with the optimal rotation axis compared to TwinSpin (Figure 9).

5 Study 2: Distant Object Manipulation

In this study, we modified the target object parameters (e.g., distance, size, and threshold) from Study 1 to evaluate each technique for distant object manipulation in VR. To assess TwinSpin's performance in this scenario, we conducted a comparative study against the baseline HOMER technique [5].

5.1 Study Design and Task

The study was a within-subjects design with an independent variable of interaction technique, which had two levels: HOMER [5] and TwinSpin. The order of the techniques was counterbalanced across participants. Each participant completed two training blocks and four testing blocks for each technique, with each block consisting of 20 task trials. The dependent variables are task completion time, total arm movement, perceived task load [20], and perceived fatigue [10] same as Study 1.

To assess the techniques, we used the docking task from Study 1, but with some modifications: the icosahedron's centroid was positioned 4 m in front of and 20 cm below the participant, and its circumradius was set to 1.5 m. The size of the chair was 28 cm × 28 cm × 56 cm—four times larger in each dimension, and the error thresholds were set to 0.1 m for position and 10 degrees for orientation. To reduce depth ambiguity, a shadow was rendered on the ground beneath the object.

5.2 Techniques

Direct HOMER [5] is a technique commonly used for manipulating distant objects [8, 19, 28]. In this approach, the user selects the object through ray-casting and uses a virtual hand (or cursor) to manipulate it. Users can employ a clutching gesture, which involves releasing and regrasping the object [57], similar to the Wrist-Arm Rotation technique described in Study 1. In this study, TwinSpin is also built upon the direct HOMER technique [5] but extends it by allowing users to rotate objects using their fingers.

5.3 Participants and Procedure

16 participants who participated in Study 1 were recruited again (5 women and 11 men, ages=18-33, M=22.18, SD=3.97) after 2-3 weeks. Since all participants had prior training experience from Study 1, only two training blocks were conducted, and a semi-structured interview was held before the experiment ended. The remaining study procedures were identical to Study 1. Each session lasted approximately 1.5 hours.

5.4 Analysis

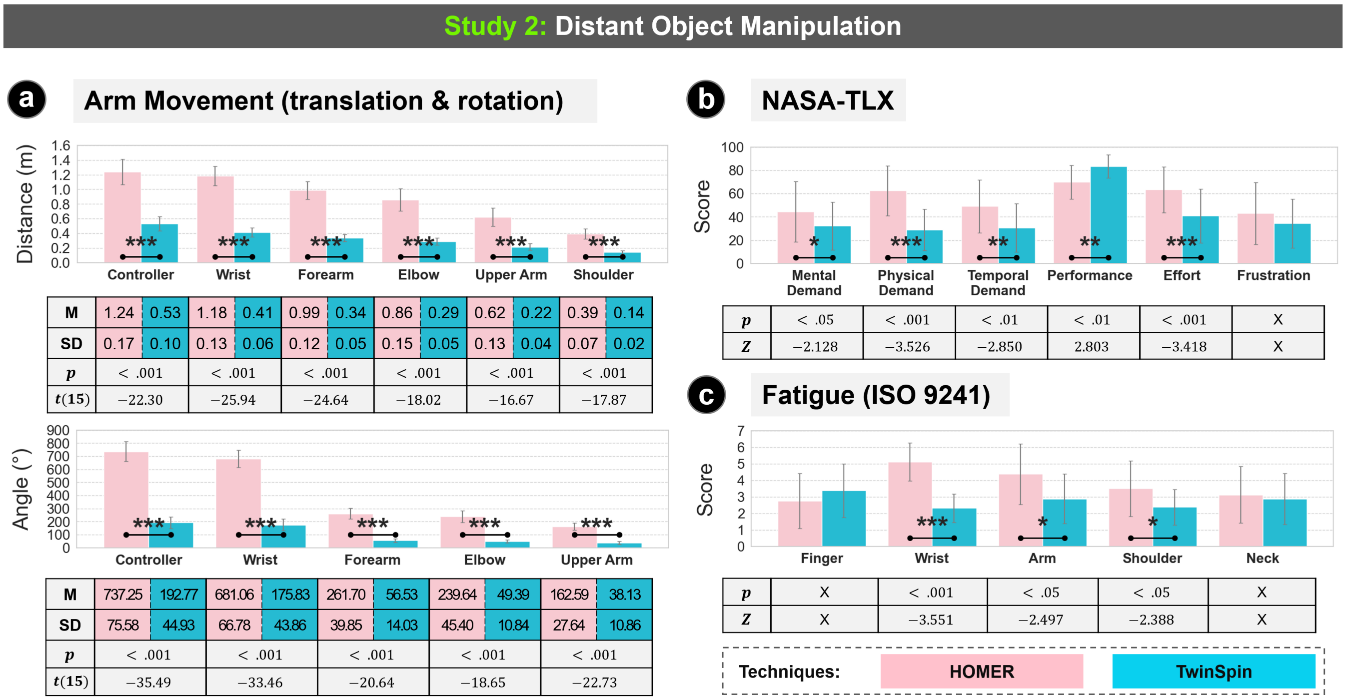
We collected a total of 2,560 data points (16 participants × 2 techniques × 4 blocks × 20 trials) from the testing blocks. Outliers were removed based on the completion time using Tukey's fences (1.5 × IQR). Both completion time and arm movement met the normality assumption (Shapiro-Wilk test, $p > .05$), allowing for a paired samples t-test to be conducted for each measure. For raw NASA-TLX [6, 20] and fatigue ratings [11] (measured on a 7-point scale), the Wilcoxon Signed-Rank test was used.

5.5 Results

5.5.1 Completion Time. The mean completion time (in seconds) for TwinSpin ($M = 5.00$, $SD = 0.84$) was **35.32%** faster than the mean time for HOMER ($M = 7.73$, $SD = 1.09$). This difference was statistically significant ($t(15) = -18.86$, $p < .001$), indicating that TwinSpin resulted in faster completion times compared to HOMER (Figure 11).

5.5.2 Arm Movement (Translation). The translation of arm movement (in meters) for TwinSpin was consistently lower than HOMER across all arm segments (wrist, forearm, elbow, upper arm, and shoulder). These differences were statistically significant for all segments ($p < .001$), indicating that TwinSpin reduced arm translation compared to HOMER (Figure 10a).

5.5.3 Arm Movement (Rotation). The rotation of arm movement (in degrees) for TwinSpin was consistently lower than HOMER



	Controller (HOMER)	Controller (TwinSpin)	Wrist (HOMER)	Wrist (TwinSpin)	Forearm (HOMER)	Forearm (TwinSpin)	Elbow (HOMER)	Elbow (TwinSpin)	Upper Arm (HOMER)	Upper Arm (TwinSpin)	Shoulder (HOMER)	Shoulder (TwinSpin)
M	1.24	0.53	1.18	0.41	0.99	0.34	0.86	0.29	0.62	0.22	0.39	0.14
SD	0.17	0.10	0.13	0.06	0.12	0.05	0.15	0.05	0.13	0.04	0.07	0.02
p	< .001		< .001		< .001		< .001		< .001		< .001	
$t(15)$	−22.30		−25.94		−24.64		−18.02		−16.67		−17.87	

	Controller (HOMER)	Controller (TwinSpin)	Wrist (HOMER)	Wrist (TwinSpin)	Forearm (HOMER)	Forearm (TwinSpin)	Elbow (HOMER)	Elbow (TwinSpin)	Upper Arm (HOMER)	Upper Arm (TwinSpin)
M	737.25	192.77	681.06	175.83	261.70	56.53	239.64	49.39	162.59	38.13
SD	75.58	44.93	66.78	43.86	39.85	14.03	45.40	10.84	27.64	10.86
p	< .001		< .001		< .001		< .001		< .001	
$t(15)$	−35.49		−33.46		−20.64		−18.65		−22.73	

	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration
p	< .05	< .001	< .01	< .01	< .001	X
Z	−2.128	−3.526	−2.850	2.803	−3.418	X

	Finger	Wrist	Arm	Shoulder	Neck
p	X	< .001	< .05	< .05	X
Z	X	−3.551	−2.497	−2.388	X

Figure 10: Results from Study 2. Error bars show standard deviations, and asterisks indicate statistically significant differences ($* : p < .05, ** : p < .01, *** : p < .001$). In the table, M = mean, SD = standard deviation, p = p-value (two-tailed). (a) Mean arm movement (translation and rotation), (b) Raw NASA-TLX scores, (c) Fatigue scores (ISO 9241).

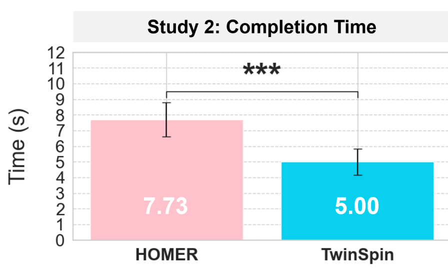


Figure 11: Mean completion time for each technique in Study 2. Error bars show standard deviations, and asterisks indicate significant differences (*: p < .001)**

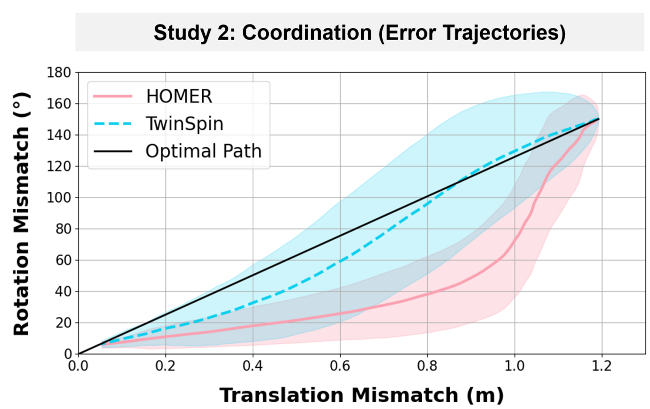


Figure 12: Error trajectories in translation-rotation mismatch space for each technique in Study 2. Error bands show standard deviations.

across all arm segments (wrist, forearm, elbow, and upper arm). These differences were statistically significant for all segments ($p < .001$), indicating that TwinSpin reduced arm rotation compared to HOMER (Figure 10a).

5.5.4 Task Load. Compared to HOMER, TwinSpin significantly reduced perceived physical demand ($p < .001$), effort ($p < .001$), temporal demand ($p < .01$), and mental demand ($p < .05$), and increased self-rated performance ($p < .01$). However, no significant differences were observed in frustration (Figure 10b).

5.5.5 Fatigue. Compared to HOMER, TwinSpin significantly reduced perceived fatigue in the wrist ($p < .001$), arm ($p < .05$), shoulder ($p < .05$). However, no significant differences were observed in finger and neck fatigue (Figure 10c).

5.6 In-Depth Analysis

5.6.1 Coordination. Since the normality assumption was satisfied (Shapiro-Wilk test, $p > .05$), a paired samples t-test was conducted. The normalized RMSD for TwinSpin ($M = 0.295$, $SD = 0.018$) showed an **23.38%** improvement over HOMER ($M = 0.385$, $SD =$

0.089). This difference was statistically significant ($t(15) = -4.69$, $p < .001$), indicating that TwinSpin resulted in more coordinated movement compared to HOMER (Figure 12).

5.6.2 Average Rotation Amount. Since the normality assumption was satisfied (Shapiro-Wilk test, $p > .05$), a paired samples t-test was conducted. The average rotation amount for TwinSpin (M = 491.92, SD = 82.84) was **25.22%** higher than HOMER (M = 392.86, SD = 59.06). This difference was statistically significant ($t(15)$ = 5.935, $p < .001$), indicating that TwinSpin invovled more rotation during manipulation compared to HOMER (Figure 8).

5.6.3 Optimal Axis Alignment Score. Since the normality assumption was satisfied (Shapiro-Wilk test, $p > .05$), a paired samples t-test was conducted. The absolute dot product for TwinSpin (M = 0.565, SD = 0.040) was **15.94%** lower than the absolute dot product for HOMER (M = 0.672, SD = 0.048). This difference was statistically significant ($t(15) = -11.001$, $p < .001$), indicating that HOMER resulted in better alignment with the optimal rotation axis compared to TwinSpin.

6 General Discussion

6.1 Ergonomic and Spatial Benefits

Interest in ergonomically designed interactions has steadily increased [21, 55]. Across both the direct and distant object manipulation studies, we found that TwinSpin significantly reduced arm movements compared to arm-based techniques. The notably greater arm rotation observed in the baseline techniques (Wrist-Arm Rotation and HOMER) occurred because these methods required not only direct arm rotation but also additional movements to reposition joints into neutral positions (i.e., clutching gestures). Wrist translation and rotation were particularly pronounced with these baseline methods; for instance, HOMER's wrist rotation amount was 387% greater than TwinSpin. The fatigue questionnaire also revealed that wrist is the primary source of discomfort among participants. P3 noted, "My wrist was the main reason for fatigue." Meanwhile, significant differences in perceived fatigue in the arm and shoulder were also evident. We anticipate that these differences may have a greater impact on user experience during prolonged interactions.

Furthermore, increased arm translation in baseline techniques suggests that arm-based techniques inherently demand overall arm repositioning rather than isolated rotation, likely due to the anatomical constraints of arm joints. This finding implies that TwinSpin has substantial potential for use in physically constrained environments, such as public transportation settings or airplane seats. While prior work [26, 46] has primarily addressed virtual hand translations in confined spaces, our findings suggest that TwinSpin may also support effective rotation under such conditions. Combined with techniques such as the Go-Go arm extension [41], TwinSpin could potentially enable full 6DoF manipulation even in constrained spaces. We also cautiously speculate that, from an accessibility perspective, TwinSpin may offer potential benefits for users with limited arm mobility or partial physical disabilities, warranting further investigation in future work.

6.2 Parallel Control of Translation and Rotation

According to Wang et al. [50], object transportation and orientation typically occur in parallel within human hand manipulation. However, arm-based techniques coupled with translation and rotation control within a single limb may force users into more sequential actions. One notable observation in Figures 8 and 12 is that arm-based techniques tend to reduce rotation mismatch earlier compared to TwinSpin. This may be due to ergonomic constraints, rotating an object with an extended arm—particularly when the elbow is stretched—can be physically demanding. As a result, participants might have performed rotations with bent arms first and then proceeded with translation. In contrast, in-hand rotation with TwinSpin is likely less affected by this limitation, as it allows users to perform translation with the arm and rotation with the fingers simultaneously.

In addition, since arm-based techniques couple translation and rotation, they frequently cause unintended translations during rotation, which can negatively affect performance. This issue became particularly evident during distant object manipulation, where the time performance gap between the arm-based baseline and TwinSpin increased compared to direct manipulation. Like HOMER, arm-based techniques for distant interaction amplify object translation beyond actual arm/hand displacements to facilitate moving objects to distant locations. As a result, they are more susceptible to unintended translations caused by arm movements during rotation. Participants explicitly highlighted this challenge. P17 remarked, "It was difficult because whenever I tried to rotate my wrist, my arm moved along, shifting the object's position unintentionally." In contrast, TwinSpin allowed users to independently control translation with the arm and rotation with the fingers, enabling more coordinated and parallel manipulation. This enlarged benefit in distant object manipulation aligns with previous findings on spherical VR controllers that leverage finger dexterity [28]. Furthermore, beyond efficiency, the coordination advantages of TwinSpin may also reflect how closely TwinSpin aligns with real-world hand use [25, 43]. Preserving this natural in-hand manipulation paradigm in virtual reality may enhance users' sense of realism and interaction naturalness [50].

6.3 Epistemic Actions

One intriguing finding is that TwinSpin's average rotation amount was larger and its optimal axis alignment score was lower than that of arm-based techniques, even though it achieved faster time performance. This might raise concerns that TwinSpin was not intuitive. However, although some participants (7 individuals) highlighted the intuitive advantage of arm-based techniques during interviews, most (13 individuals) still reported confidently rotating objects as intended with TwinSpin. Thus, we suggest one possible explanation for this seemingly contradictory observation; some participants might have been utilizing epistemic actions [30]—physical actions taken to make a problem easier to think about, rather than as direct progress toward a goal—to reduce the cognitive load (e.g., rotating a Tetris piece multiple times to see how it fits, rather than mentally rotating it). This behavior may arise due to the known cognitive difficulty associated with mental rotations [38]. For example, P2 noted, "When quickly rotating near the target, I'd see the green

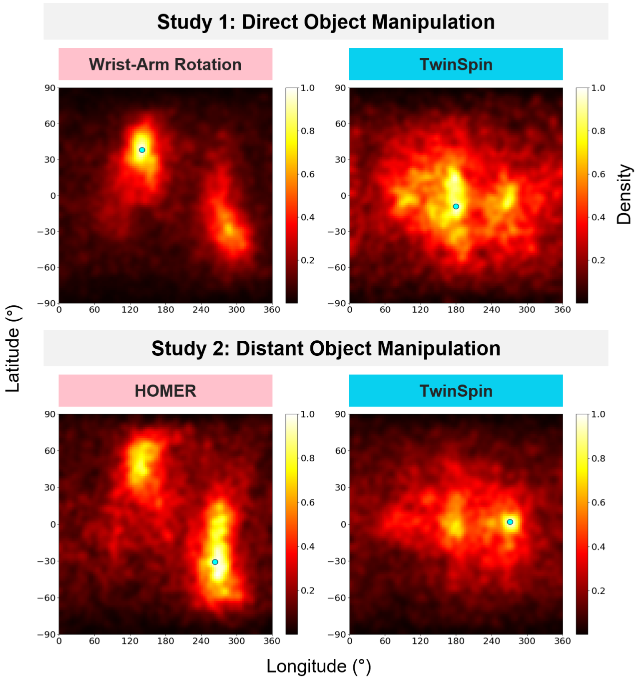


Figure 13: The preferred rotation axes used in each technique. The cyan marker indicates the highest density.

indicator (capture indicator), which helped me estimate how much I needed to rotate." We speculate that such epistemic actions were feasible because TwinSpin has a relatively low interaction cost, as evidenced by its lower perceived physical demand and effort. This low cost might have encouraged an exploratory, trial-and-error approach, minimizing reliance on mental simulation. P3 explained, "HOMER was challenging, so I had to plan rotations in advance. TwinSpin has full access to the whole 360 degrees, and I usually didn't think that much—I immediately rotated." Similarly, P4 stated, "With TwinSpin, it was easier on my hands because I just needed to move my fingers, and even if I made mistakes, recovery was very quick." This was consistent with lower perceived mental demands for distant manipulation tasks using TwinSpin.

On the other hand, other explanations should also be considered. The preferred rotation axes might have influenced TwinSpin's nonoptimal rotations. To investigate this, we conducted an axis distribution analysis (Figure 13). A rigid body's continuous orientation change in 3D space can be represented by a series of small rotations, each with a rotation axis. A rotation axis can be represented by latitude and longitude, and Figure 13 shows the density of these rotation axes. The high-density areas in the heatmap show that particular rotation axes were predominantly used. It revealed similar patterns in both direct and distant tasks, suggesting the presence of preferred rotation axes with TwinSpin. However, Wrist-Arm Rotation and HOMER also appeared to have their own preferred rotation axes, likely due to natural joint constraints and preferred joint movements. Thus, preferred rotation axes alone cannot fully explain TwinSpin's nonoptimal rotations, although they may lead to a rotation amount greater than the theoretical minimum. Lastly, overshoots—possibly caused by TwinSpin's trackball gain settings—may have contributed to its rotation inefficiency.

7 Limitations and Future Work

This paper compared arm-based techniques with TwinSpin, which enables finger-based rotation, and focused on investigating how the introduction of in-hand rotation in VR affects arm movements and user behaviors. However, dynamic non-isomorphic rotation mapping [14] was not considered in the current study, both for the baseline arm-based techniques and TwinSpin. We initially anticipated users would use the trackball for the coarse control phase and rely on the wrist for the fine control phase, as using a constant-gain trackball for fine adjustments sometimes led to overshoots. However, some participants reported successfully using the trackball even for fine control during the study. For example, P17 said, "I also used the trackball for detailed control." Thus, we cautiously expect that adjusting the trackball gain for individual users and integrating dynamic mapping based on finger movement speed could improve precision and enhance performance. Likewise, applying amplification methods [52] to arm-based techniques would possibly reduce the required arm movements to some extent. Nevertheless, due to the inherent coupling between translation and rotation, we expect TwinSpin to retain its advantage. Future work could evaluate TwinSpin and arm-based techniques with gain acceleration to clarify this effect.

Furthermore, beyond controlled settings, future research should investigate TwinSpin's usability in more diverse VR use cases. These scenarios will often involve objects with diverse shapes and sizes, as well as tasks requiring axis-constrained rotations (e.g., tightening a bottle cap), which were not covered in the current study. Additionally, using TwinSpin in practical scenarios may influence user immersion and presence. Follow-up research could address these factors by evaluating TwinSpin across a range of VR interaction contexts—for instance, assembly tasks—and assessing user experience using instruments such as the User Experience Questionnaire (UEQ) [32].

Finally, beyond object rotation in VR, the concept of TwinSpin holds promise for broader application scenarios. For example, it could be leveraged for viewpoint control in VR-based 3D modeling or virtual cinematography. More exploratory directions include 3DoF end-effector control for a robotic arm, as well as single-handed drone teleoperation in both physical and VR flight simulations.

8 Conclusion

In this work, we presented TwinSpin, a VR controller enabling full 3DoF in-hand rotation by manipulating two embedded trackballs based on the intuitive metaphor of rolling a virtual ball in-hand. Through user studies involving both direct and distant object manipulation tasks in VR, we showed that TwinSpin significantly reduces task completion time and arm movements (translation and rotation) compared to conventional arm-based techniques. Participants also reported lower perceived physical demand and effort, as well as reduced perceived fatigue in the wrist, arm, and shoulder when using TwinSpin. Furthermore, in-depth analyses revealed that TwinSpin allows for more parallel control of translation and rotation compared to arm-based techniques. In addition, distinct rotational trajectories were observed, and users appeared to adopt different manipulation strategies when using TwinSpin; however, further investigation is required. A deeper understanding of TwinSpin's control space and users' strategy with it may enable better design iterations of TwinSpin. We hope this research encourages further exploration of finger dexterity in VR controller design to expand the interaction space.

Acknowledgments

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