Stick-To-XR: Understanding Stick-Based User Interface Design for Extended Reality

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ABSTRACT

This work explores the design of stick-shaped Tangible User Interfaces (TUI) for Extended Reality (XR). While sticks are widely used in everyday objects, their applications as a TUI in XR have not been systematically studied. We conducted a participatory design session with twelve experts in XR and human-computer interaction to investigate the affordances of stick-based objects and how to utilize them in XR. The results led us to develop a taxonomy of stick-based objects' affordances in terms of their functions and holding gestures. Following that, we proposed four types of stick-based XR controller forms and discussed their advantages and limitations. In the end, we juxtaposed twenty-six existing XR controllers against our proposed forms and identified Landed (Cane) Stick, Thin Stick's flexible usages, and Modular Design as the major opportunities that remain unexamined yet for stick-based XR TUI design.

CCS CONCEPTS

• **Human-centered computing** → **Interface design prototyping**; **Participatory design**; **Virtual reality**.

KEYWORDS

Tangible User Interface, Extended Reality, Stick Shape, Device Form Factor, Taxonomy, Handheld Device

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1 INTRODUCTION

A Tangible User Interface (TUI) is a User Interface (UI) that enables the interaction with digital information through physical objects and materials. TUI expands the scope of Human-Computer Interaction (HCI) by diversifying user interaction methods beyond traditional keyboard, mouse, and touchscreen paradigms. With the advancement of TUI, researchers have been exploring the relationship between shapes and hand grips to inform TUI design. One of the most recent works in the field is from Serrano et al., who explored how the shapes of handheld freeform devices affect interaction [27]. Other studies focused on shape-changing objects [24–26]. Researchers have also studied hand gestures with objects [11, 29, 41].

In this work, we study shape design and hand-grasping gestures on the shape with specific exploration of the **stick** shape and how to adopt this form into Extended Reality (XR) UI design. Here, we define a stick as an object with a long, thin, and cylindrical shape. We are particularly interested in stick shapes instead of compact shapes like balls or disks because not only can sticks be held in a user's hand, but they can also contact or link to other objects, ground, or walls. As we all know, sticks are a common shape used in daily objects. This shape can be found in a diverse range of contexts, including our professional lives (in pens), education (teaching sticks), sports (rackets), and general household items (kitchen utensils and tools).

As anticipated, a stick shape is widely adopted in HCI and XR as a TUI. Most commercial Virtual Reality (VR) controllers are shaped as short sticks to work with users' hands, such as the Meta Quest or HTC Vive controllers [5, 35]. Academic research has also suggested diversified XR controller designs of the stick form factor. For instance, Harders et al. used a sharp-tipped pen to perform high-precision operations in Augmented Reality (AR) [14]. As another example, Zhao et al. proposed a cane that is attached to programmable brakes to simulate touching virtual objects for blind users' VR experience [40]. Each of these designs adopted some affordance of a stick shape, such as Harders et al.'s precision interface used a thin stick's tip for accurate pointing [14], and Zhao et al.'s VR cane works as an extension for the user's arm to detect the environment [40]. However, there is no study yet that has systematically explored the design space of the stick-based TUI in XR. There are more usages of stick shape design that are found in daily usages, but not fully adopted in XR yet. For example, its feature of supporting and balancing the body might be helpful for stable operations in XR, and its leveraging feature might be used to save effort or reduce workload. Thus, we aim to explore and understand stick-based UI design for XR in this work.

The three research questions (RQs) that guided this work are:

RQ1. Stick-Based Objects' Affordances: What daily objects are stick-based, and what are their functionalities and holding gestures while being used?
RQ2. Design Insights of Stick-Based Design in XR TUI: What variations of stick-based interfaces can be integrated into XR TUI, and what are their advantages and limitations?
RQ3. Design Opportunities: What are the potential stick-based XR TUI designs remain unexamined?

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To address these questions, we conducted a participatory design session with twelve experts in XR and HCI. Participants brainstormed on the affordance of daily stick-based objects and designed stick-based XR controllers on paper. We collected participants' brainstorming, design, and interview responses and performed open, axial, and selective coding. To clarify the affordances of stick-shaped objects (**RQ1**), we developed a taxonomy for stick-based objects in terms of functionalities (Section 4.1) and holding gestures (Section 4.2) while also discussing the relationship between a stick object's functions, gestures, and forms (Section 4.3). To provide insights into stick shape designs in XR (**RQ2**), we first presented the design of four forms of stick-based XR controllers (Section 5) and elaborated on the advantages and limitations of these forms (Section 6). Following that, we identified five promising design opportunities (**RQ3**) that remain unexamined by comparing twenty-six existing works against our proposed forms (Section 7).

2 RELATED WORK

TUI emerged in 1997 [15] and has been developed over the years [28]. Our work contributes to TUI knowledge by studying stick shapes on their functionalities, hand-grasping gestures, and applications in XR.

2.1 Shape Studies

We study the stick shape, especially identifying how their diverse shapes (such as length or thickness) afford distinct functionalities. With this, we can further infer how stick-based TUI can solve existing issues in XR. To the best of our knowledge, we have not seen shape studies for stick-based objects. However, some studies have cast light on freeform or shape-changing designs. For example, Majken et al. explored shape-changing interfaces and identified eight types for shape transformation [24]. Roudaut et al. proposed the notion of "Shape Resolution" to describe the flexibility of shape-changing device [26]. As another example, Serrano et al. arranged participatory design sessions to understand how shape affected interaction for freeform handheld devices [27]. They provided insights such as the trade-off between holding and interacting and the benefit of using metaphors and docking for feature discoverability. We used a similar participatory design method to involve experts in brainstorming and prototyping stick-based XR controllers and elicit their insights on the design space.

2.2 Grasp Gesture Studies

In our study, we are also interested in analyzing the gestures for interacting with stick-based objects. This could inform XR controller designs regarding the appropriate types of sensors and control and optimal locations to embed them. Regarding hand gesture studies, Cutkosky proposed a grasp taxonomy [11], which discussed various hand grasping types for more precision or more power for compact or long-shaped objects. Zheng et al. later examined these grasping gestures with housemaids and machinists' daily activities and identified the most common grasp gestures for these activities [41]. Feix et al. [12] provided a GRASP taxonomy that incorporates a number of previous works to classify grasp gestures based on opposition type, virtual finger assignments, power/intermediate/precision grasp, and thumb position. Sharma et al. studied single finger gestures when a user grasps an object [29]. Zhou et al. proposed Gripmarks [42] to detect the handheld object shape by the user's griping gesture and thus construct an interactable surface on top of the handheld object. These works have enriched our understanding of grasping gestures for objects typically held in hand. However, our work is uniquely focused on stick-based objects for XR controller design. We present previously unexplored areas in gesture studies, such as different numbers of stick objects as hand controls, and the opportunities of hosting inputs with different gestures for different stick forms.

2.3 Stick-Based XR Controller Studies

There are a variety of existing XR controller designs that adopt stick shapes. For instance, Microsoft Research proposed VR canes for blind or low-vision users to experience virtual environments [32, 40]. Some researchers explored stick-shaped handheld controllers that are shape-changing to simulate weight and drag (e.g., [21, 30, 34, 36, 39]). Strasnick et al. considered linking two controllers in different dynamics [33]. We will refer to more existing stick-based XR controllers in Section 7, where we compared them against the forms of XR controllers our participants proposed, and discussed the potential applications of stick-based design in XR that have not been explored.

3 METHOD

We invited 12 participants (6F/6M, aged 25.6 on average, 4 in the United States and 8 in China). We recruited participants with expertise in XR, hardware design, and computer-aided design. Table 1 summarizes participants' self-reported expertise. They participated in the study in groups of 2 or 3. Four participants (P4 - P7) participated online through Microsoft Teams[1], while others had in-person sessions (Figure 1-a). The study consisted of a 1-hour participatory design session with four activities (denoted as Activity 1-4 hereafter and in Figure 1).

Table 1: Participants' self-rated expertise level in Extended Reality (XR), Tangible Design/Industrial Design (TD/ID), and Computer-Aided Design (CAD). Ratings were from 1 to 5, with 1 being "no knowledge" and 5 being "expert".

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
XR	4	4	3	4	4	4	5	2	4	4	4	4
TD/ID	2	4	3	4	4	4	4	2	2	2	3	1
CAD	1	1	2	4	5	4	4	1	1	1	2	1

The study began with participants listing out names of stick-based objects to the best of their abilities (Activity 1). These answers were displayed in real-time on a shared screen using the Mentimeter presenter tool[2], allowing participants to draw inspiration from one another (Figure 1-b).

In Activity 2, the participants were asked to write down the affordances of stick-based objects, considering their usage, holding method, and how they contact other objects. For instance, one of their answers was "[Hammer] Usage: Break stuff / push stuff

[1] https://www.microsoft.com/en-us/microsoft-teams/group-chat-software
[2] https://www.mentimeter.com/

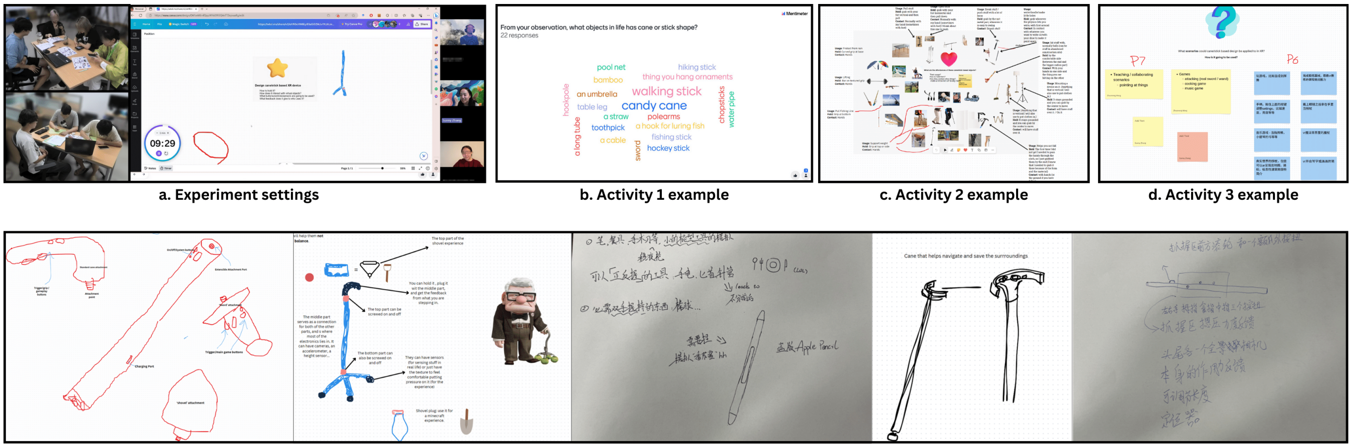


Figure 1: The participatory design study. a: The experiment setting (in-person or online). b-e: Participants' response examples for each of the 4 activities.

with a lot of force; Hold: grab by the not metal part, wherever it is easy to swing; Contact: stuff to be smashed"(Figure 1-c). Participants' answers are also posted on a shared screen to inspire each other. A collection of stick-shaped objects was provided to facilitate participants' thinking.

The first two activities aimed to familiarize participants with various stick-based objects and their associated affordances, while the following two activities guided the participants in exploring the application of these objects in XR interaction. Activity 3 asked the participants to write down scenarios where stick-based designs could be employed in XR interaction (Figure 1-d). For example, P5 answered, "*A cane stick can be used so people have something to hold on to during certain experiences that will help them not fall or lose balance. (Like) a hike experience; (or) something that requires walking (and people need extra help).*" The experimenter discussed the answers with the participants and asked follow-up questions as necessary.

Lastly, participants were instructed to create a stick-based XR controller design on paper or a whiteboard in Activity 4. We provided a set of design aspects to prompt more concrete creations: 1) grip method, 2) interaction with virtual objects, 3) buttons / controls / sensors, and 4) the feedback it provides to the user. Participants were given approximately 15 minutes to complete their designs individually, after which they presented and explained how their designs addressed the four aspects. They were also asked to compare the pros and cons of their designs with freehand control and typical XR controllers like the Meta Quest controller. They could comment on each other's design during the discussion. The experimenter posed follow-up questions as necessary. Figure 1-e presents some examples of the participants' designs.

Participants' textual responses, sketches, and conversation recordings were analyzed through open coding, axial coding, and selective coding. We present our preliminary findings in the next section.

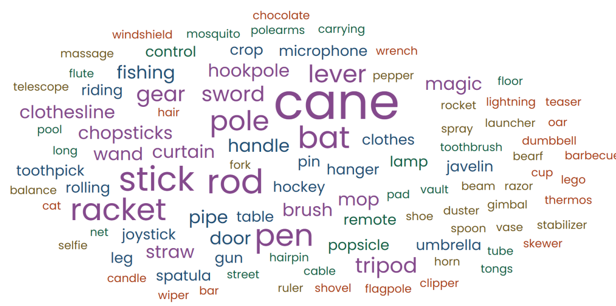


Figure 2: The word cloud of stick-based objects that participants mentioned in Activity 1. The same item with different names was merged to reflect the mentioned frequency (e.g., "walking stick" and "cane" mean the same, thus represented both as "cane" in the word cloud result).

4 STICK-BASED OBJECTS AND THEIR AFFORDANCES

Our **RQ1** focuses on the affordances of stick-based objects, particularly what daily objects are stick-based and their functionalities and holding gestures. To address the **RQ1**, we first present the stick-based objects listed by our participants in Figure 2. The objects most mentioned include "cane", "racket or bat", "pen", and "gear lever". From our analysis of the stick-based objects and participants' opinions of their affordances, we present the taxonomy of stick-based objects' affordances in terms of functionality and holding gesture and conclude the relationship of function, gesture, and form design for stick-based objects in this section.

4.1 Functions

As an elongated shape, a stick is commonly adopted in object designs to foster a relationship between two entities, one of which is often the user's hand. However, there are a wide range of variations in how stick objects facilitate this connection. Here, we present a

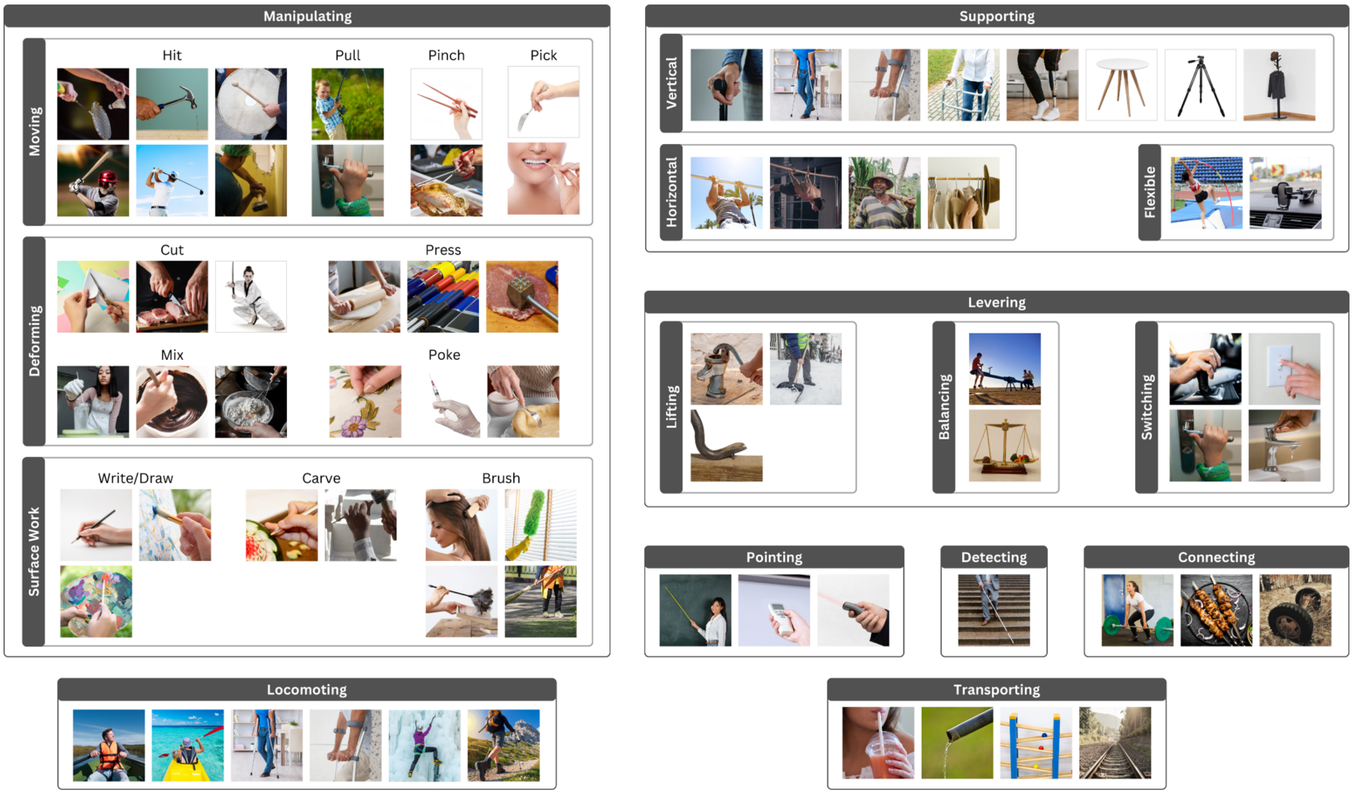


Figure 3: The functions of stick-based objects.

taxonomy of stick-based objects' functions and example objects in Figure 3.

The predominant category is the stick-shaped object as a tool to alter other objects. We refer to this category as *Manipulating*. It contains subcategories of *Moving* (through *Hit, Pull, Pinch or Pick*), *Deforming* (via *Cut, Press, Mix or Poke*), and *Surface Work* (including *Write/Draw, Carve, or Brush*).

Another principle category is *Supporting*, where the stick is used to resist gravitational force for a user or an object. This entails *Vertical*, where the stick stands on the ground to support another object placed atop it, such as canes or table legs; *Horizontal*, where the stick is placed horizontally, enabling objects to hang on it, such as pull-up bars or coat hanger bars; and a more special type of *Flexible*, where the stick can change position during its usage to support the object while simultaneously offering some degree of freedom. One instance of this is the pole for pole vaulting. Alternatively, some products combine multiple stick-shaped parts with mechanical structures to provide support while being flexible. An example is the flexible phone stand that holds the phone in place while allowing the user to adjust its position. We will discuss the relationship between flexibility and support later in depth in Section 6.

Another frequently mentioned type of function is *Levering* for sticks that are fixed or attached to a rotational joint. This function hosts three different subsets: *Lifting*, for the user to lift an object with little effort, such as crowbars; *Balancing*, to equilibrate two objects on its two ends, such as balance scales; and *Switching*, whereby the stick can be moved to a predetermined position to manipulate a function, like gear levers.

There is also a category of *Pointing*, where the user utilizes a stick to indicate a specific spot on an object. This could be executed by lightly touching the object's surface with the stick's tip (like teaching sticks) or by emitting a laser beam from the tip of the stick (like remote controls). Furthermore, some objects serve the function of *Locomoting*, which are used one per hand and touch the ground alternately to aid the user's movement forward, such as paddles, hiking sticks, and ice axes. Moreover, there are miscellaneous types of functions for special purposes, including *Detecting* (e.g., a white cane for detecting the objects in the path), *Connecting* (e.g., a barbell bar with bumper plates attached at two ends), and *Transporting* (e.g., a drinking straw for carrying the beverage to user's mouth).

Note that some stick-shaped objects fulfill multiple functions at the same time. For example, canes provide both functionalities of Supporting and Locomoting.

4.2 Gestures

While gripping gestures of a general handheld device have been widely discussed [11, 12, 41], prior research has not yet delved into the nuances of stick-based objects and the unique contexts where multiple sticks are in hand, or two hands operate a single stick. Depending on how many sticks the user operates and the form of the stick(s), whether it is thin or thick, long or short, or attached to another stick, the holding gestures may vary. Here, we organize and

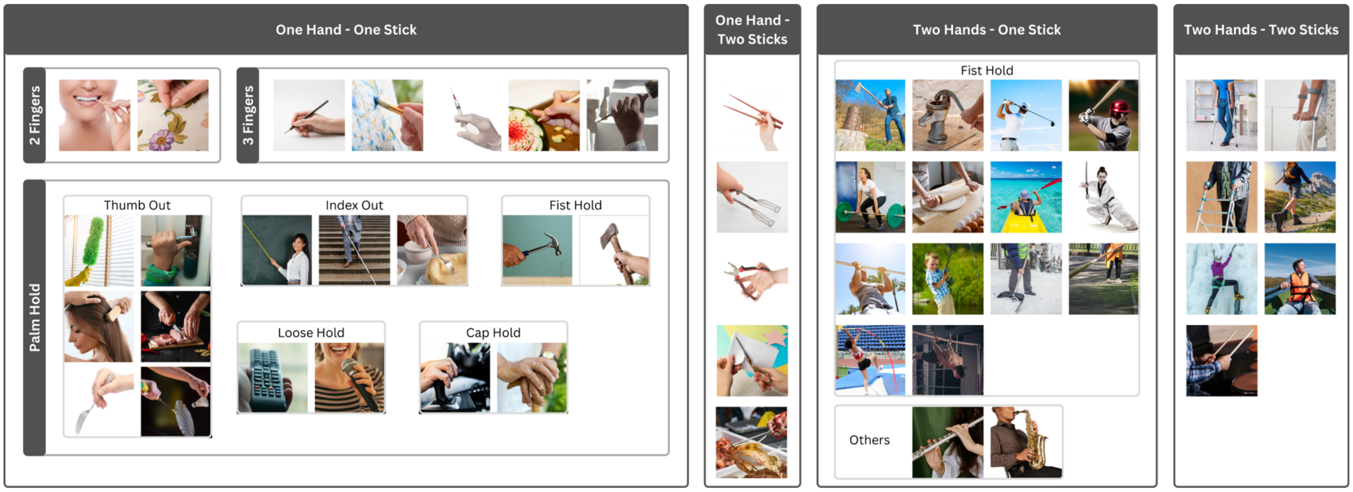


Figure 4: The holding gestures with stick-based objects.

illustrate the observed gestures in Figure 4. Regarding how many stick-shaped objects a hand controls, we categorize the gestures into *One Hand - One Stick*, *One Hand - Two Sticks*, *Two Hands - One Stick*, and *Two Hands - Two Sticks*.

One Hand - One Stick is the most important gesture category because this category's gestures can be considered fundamental ones that can extend to gestures in the other three categories. Depending on what parts of a hand are used to hold the stick, this involves gestures of *Two Fingers*, *Three fingers*, and *Palm Hold*, which is the gesture that involves the palm to hold as opposed to fingers for gripping the stick. We have not seen any common stick-shaped objects that need four or five fingers to hold without touching a user's palm. For the Palm Hold, there is *Fist Hold*, the gesture to grip tightly like a fist. There are also *Thumb Out* and *Index Out*, which are almost like Fist Hold, but either the thumb or the index finger extends out, resting on the stick. Another gesture is *Cap Hold*, where the hand wraps on the end of a stick like a cap. Sometimes, a user holds a stick loosely in their palm, and their fingers are loosely touching the stick; we call it *Loose Hold*.

In some cases, a user holds two sticks in a single hand (*One Hand - Two Sticks*). Some tools have two sticks connected together, either from the middle (e.g., scissors) or from the end (e.g., tongs). In this case, the holding gestures are similar to a Palm Hold. A special case is the use of chopsticks, akin to the Three Finger gesture employed in holding a pen, but with one more stick between thumb and index finger or thumb and ring finger. This gesture requires more dexterity from the fingers. It should be noted, however, that we haven't encountered any instances of a user manipulating three or more sticks using a single hand.

A stick can also be held by two hands (*Two Hands - One Stick*). This often happens when a user requires a firm hold to execute powerful movements, such as swinging a racket or lifting a barbell. So often, the two hands are both using Palm Hold, especially Fist Hold. However, in scenarios requiring delicate maneuvering, such as playing flute, all ten fingers are generally employed to lightly secure the instrument while maintaining dexterity to manipulate its buttons.

Lastly, some stick-shaped objects are used in pairs as *Two Hands - Two Sticks*. This category essentially serves as a bimanual extension of One Hand - One Stick but needs the coordination of both hands to perform a task together.

4.3 Relationship of Functions, Gestures, and Forms

The designers of XR handheld controllers essentially select forms that can afford the functions of the XR interaction with suitable holding gestures. So, it is important to understand the relationship between functions, gestures, and forms. From analyzing the affordance of stick-based objects in people's daily life, we did not see a clear connection between function and gestures. In fact, the same function can be conducted with different gestures. As shown in the first column in Figure 5, the user can hold the craft knife, duster, and paint bush all with the finger hold gesture but perform totally different functions. Similarly, the user performs the cut action using bladed sticks but with finger hold (Two Fingers or Three Fingers), Palm Hold, and double hand hold (Two Hands - One Stick) gestures, as illustrated in the first row of Figure 5. Here, we can see the functionality of a stick-based tool is determined by how it contacts other objects, such as with a blade, brush, or paintbrush. While, the holding gesture when using a stick-based tool is determined by how the form contacts the hand. For example, thin sticks are held with fingers, thicker sticks are held with fingers plus the palm to hold firmly, and longer sticks can be held with two hands. If the stick has a groove design on it, it also informs the user's holding gesture, which is indicated in the Mold-It study [27]. We conclude the relationship between forms, functions, and gestures in Figure 6. Overall, the form where the stick-based object contacts the user's hand(s) affects the gesture, while the form where it contacts other objects affects the function.

One constraint worth mentioning is that the holding gesture also limits the user's movement when holding the stick. Using a

Gesture / Function	Finger Hold (One Hand - One Stick)	Palm Hold (One Hand - One Stick)	Double Hands Hold (Two Hands - Two Sticks)
Cut			
Brush			
Paint			

Figure 5: Comparing functionalities and gestures in stick-based objects.

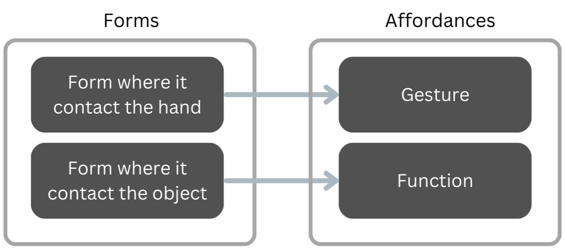


Figure 6: The relationship between forms and affordances for stick-based objects.

double hand hold gesture, a user mostly conducts big movements like swinging, whereas using a finger hold gesture, a user can conduct smaller but more complicated movements like drawing or carving patterns on paper. This movement limitation can influence the functionality of the stick. There are some interesting trade-off properties across form, gesture, and movement. We will discuss them in the following section.

5 FORMS OF STICK-BASED CONTROLLERS FOR XR

To answer **RQ2**, design insights of stick-based design in XR TUI, we analyzed participants' designs of stick-based controllers for XR. In this section, we outlined the noticeable patterns derived from these designs. In all, we have categorized participants' designs into four forms: **Standard Stick**, **Long Stick**, **Thin Stick**, and **Modular Design**.

5.1 Standard Stick

The most basic form is a short stick held in hand, which we call **Standard Stick** form. Two gesture patterns merged for this form. The most frequently mentioned design is the **Thumb Out** gesture pattern of the Standard Stick (proposed by P2, 3, 4, 7, 8, and 11), with the thumb resting on the side and the other four fingers wrapping around the stick (Figure 7-A.G1). In the figure, we identify the participants' suggested placements for input controls on the controller design. Red, green, and blue areas represent the viable areas for the control implementation of thumb, index, and middle fingers, respectively. For the Thumb Out form, the primary controls are placed for the thumbs, meaning that it can hold multiple controls or more complicated controls such as a touchpad. The index and middle fingers can also have simple controls. P11 also proposed another gesture pattern of the Standard Stick - the **Index Out** form, as shown in Figure 7-A.G2, for which the index finger is straight on the stick, used to press the stick. In this form, the index finger holds the main control. P11 proposed a button and a scrolling wheel for the index finger. However, our audiences can configure the controls according to their specific requirements.

Moreover, regardless of the selected gesture pattern, the Standard Stick form can also adopt a **Weight Changing** design variation that uses mechanisms to change the center of weights, thus simulating different holding feelings (P8 and P11, Figure 7-A.V1).

Participants suggested a wide range of usage of the Standard Stick form, such as simulating specific tools like a sword (P2 and P4), peddle (P11), wand (P7), and fishing rod (P3 and P8). This form is also adopted by major commercial VR controllers [20, 35].

5.2 Long Stick

By extending the length of the Standard Stick, it evolves into what we refer to as a **Long Stick** form. When a user positions this Long Stick such that it makes contact with the ground like a cane, we identified it as the **Landed (Cane) Stick** form (Figure 7-B1). This form is the second most prevalent form from participants' submissions. In this form, the user's movement is limited in that the user basically can only orbit the hand-holding part around where it touches the floor, but the user also gets support from the ground, which can potentially help the user to keep balance or make the hand movement more stable. This form has multiple gesture patterns depending on where the long stick extends from the short stick that the user holds. It could be from the end (P6, Figure 7-B1.G1), from the middle (P2, Figure 7-B1.G2), from the top (P2, 4, 5, 10, Figure 7-B1.G4, B1.G5). P5 even suggested a U-shaped connection like a shove handle (Figure 7-B1.G3). P2 mentioned the stick fixed on a rotational joint to simulate the gear lever (Figure 7-B1.G6). Each of these variations has distinct holding gestures and potential placement areas for buttons and controls, as illustrated in Figure 7. Participants usually assign more controls to the thumb, such as a big touchpad (P9 and P10) or a T-shaped button bar (P6, Figure 7-B1.G1). However, B1.G3 and B1.G6 use tight gestures so that fingers are limited from manipulating extra controls in these two variations. For the usage of the Landed Stick form, participants commonly pointed out that it can be used for accessibility, specifically in assisting users with mobility challenges while using the XR experience (P5, 6, and 10). P6 also suggested that the Landed Stick form offers stability, which could benefit tasks like environment scanning.

Alternatively, the user can also use it by lifting it in the air, which we refer to as the **Lifted Stick** form (Figure 7-B2). This category, however, has not been explored in academia. We postulate the reason is that the Standard Stick can also virtually simulate a

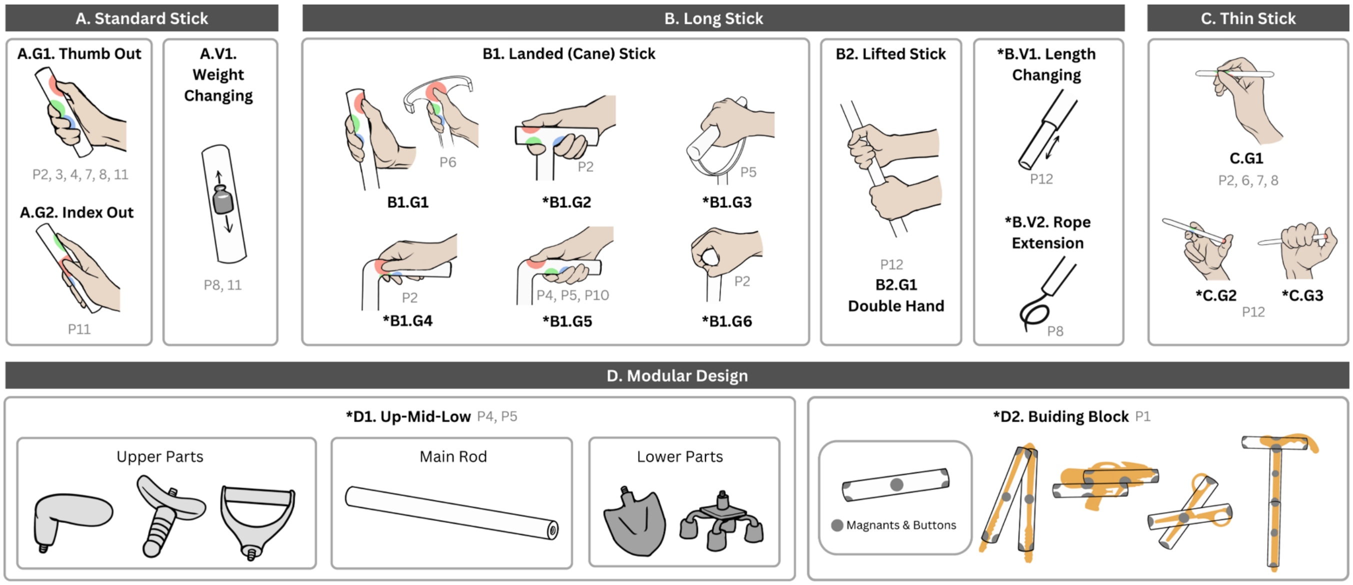


Figure 7: The forms for stick-based designs in XR Controllers, their gesture patterns (denoted as G#) and variations (denoted as V#), and the participants from whom the designs originated (denoted as P#). Red, green, and blue areas represent areas where controls can be put for the thumb, index, and middle fingers, respectively. The underexplored designs are with a prefix *.

lifted long stick in XR (like simulating a virtual saber). A physical long stick may only be needed when users need to touch or detect specific objects at its tip or to provide the real sensation of waving a long stick. Pertaining to this form, one of our participants (P12) mentioned a design where the user uses two hands to hold the stick-based controller (Figure 7-B2.G1), where controls and pressure sensors can be located on the stick according to the user's grip.

Furthermore, both the Landed or Lifted form could also include a **Length Changing** variation (P2, 11, and 12, Figure 7-B.V1) to accommodate various needs. Besides incorporating only a rigid stick, P8 proposed a **Rope Extension** variation to extend the stick's length by pulling out a rope (Figure 7-B.V2). She felt this provided a unique dynamic of "controlling a soft element with a rigid one," and it contrasted the rigid strength of the stick with the flexibility of the rope.

5.3 Thin Stick

The **Thin Stick** form is a thin, light stick that can be held between fingers (rather than having to use the palm to hold it steadily). Participants usually mentioned holding it as a pen (P2, 6, 7, and 8, see Figure 7-C.G1) and using its tip for accurate selection. Its end then can embed a button to press and/or be used as an eraser. However, P12 pointed out that compared to the Standard Stick, this form is more *versatile* because the user can easily manipulate it between fingers, thereby enabling them to alter their gestures to simulate different tools. For this purpose, P12 proposed a symmetric design where the stick's both ends work interchangeably no matter whether the user is holding either end, front or back. He proposed this to be applied to, e.g., medical lab simulation, where the operator often uses tools, such as syringes (held as Figure 7-C.G2) or pipettes (held as Figure 7-C.G3). He pointed out that conventional VR controllers are only able to be held in Thumb Out form and are not able to facilitate such needs. Besides the versatility, another benefit of this form is that it is lightweight and easy to carry. As P11 said, it could be attached to XR glasses.

Control-wise, participants mainly adopt squeezing and tabbing gestures (P7 and P11). This could be because the Think Stick form is too small to have many buttons on its body. As P7 stated, "*because of its lightweight, it sacrifices the clarity of buttons. Whereas (conventional) controllers are bigger, and the user can touch each distinct button easily.*" However, this form leverages the mobility of both the fingers and the wrist and enhances flexibility in movement. Hence, its potential usage spans fields that need precision and extensive motion. Participants pointed out it can be used in scenarios like office work (P7), drawing (P6), medication (P12), and teaching (P7).

5.4 Modular Design

Some participants also applied a **Modular Design** in their work. We discovered two types of Modular Design from participants' submissions. Firstly is a **Up-Mid-Low** combination design from both P4 and P5 (Figure 7-D1). It features interchangeable upper and lower segments that screw to the main rod. The upper segments are designed for diverse handling styles (e.g., sword handle or shove handle). The lower segment can accommodate various types of end pieces, such as shove head or tripod end, and it is capable of hosting sensors that can potentially detect when the cane strikes the floor. The main rod contains batteries and is the center of weight.

On the other hand, participant P1 introduced the **Building Block** design, which comprises numerous short sticks with magnets (Figure 7-D1). These sticks can be assembled in a multitude of configurations to cater to diverse needs. For instance, a pair of sticks can be connected at the center to create a scissor-like motion, or multiple sticks can be assembled to replicate the form of a gun.

6 ADVANTAGES AND LIMITATIONS OF FORMS

In the previous section, we derived four forms of stick-based interfaces that can be integrated into XR TUI. This section continues to investigate the design insights of stick-based design (**RQ2**) by analyzing the advantages and limitations of the variations summarized in the previous section. Table 2 provides a summary of the advantages and limitations of forms.

6.1 Hosting Input Controls and Sensors

Participants commonly designed their buttons or controls for the thumb, index, and middle fingers. In particular, thumbs are given a larger operation area, such as a T-shaped space (P6, illustrated in Figure 7-B1.G1) or a touchpad (P10). This is consistent with findings from Sharma et al. [29], where they found these three fingers are considered much easier to perform a vast majority of gestures with than the ring and little fingers. In Section 5, we illustrated the positions on each stick form where control buttons could be placed in Figure 7. In general, the thin stick has the fewest opportunities to put many buttons due to its size. Thus, for thin sticks, participants mainly designed tab or squeeze interactions like on the Apple Pencil (P7, P11) or buttons along its body where the thumb might touch (P6). P7 stated that this form sacrificed control clarity for portability. Further, when the thumb, index, and middle fingers hold the thin stick, they are locked in place. As Serrano et al. revealed from handheld design [27], there is a trade-off between holding and interacting. Whereas in the Standard Stick or Long Stick forms, the stick is largely managed by the user's palm and the two less flexible fingers, which frees up the thumb, index, and middle fingers to perform more intricate interactions on controls like on touchpads, thumbsticks, or sliders.

Besides receiving the user's hand input, it is also important for an XR controller to interact with other objects. Thus, sensor placement is important. From the study results, we did not observe any obvious difference among different stick forms for hosting sensors. Participants generally proposed the controller would need positional and rotational tracking (P4, 5, 8, 11, and 12) to locate itself in VR or the digital twin space in AR. It can also have sensors on the tip in order to detect events such as the cane hitting the floor (P3 and P6) or the pen touching an object to get its color (P6). Moreover, XR could be more fun and powerful with ubiquitous computing, where stick controllers can contain sensors to detect smart objects and trigger reactions, which could be used in cases like tangible classrooms for kids or sports practice rooms.

6.2 Power and Precision

Previous studies have elucidated the relationship between the size of a handheld object, the associated holding gesture, and task precision: a decrease in object size can enhance dexterity and involve fewer fingers in the task execution, while an increase in object size leads to a power boost and necessitates the use of more fingers and likely the palm in the holding gesture [11, 41].

Our observation of stick-based tools aligns with that finding. Tools fulfilling functions of Moving, Deforming, Supporting, and Locomoting categories usually require greater power and larger dimensions. They often feature thicker or wider tips where they contact other objects, such as the striking area of rackets or hammers. Conversely, tools bearing functions of Surface Work and Pointing necessitate more precision and exhibit smaller dimensions. Such tools are often equipped with thinner or sharper tips, such as pens or scalpels. However, tasks of the same type of function can vary in their demand for precision or power. Considering the Deforming-Cut function as an example - the sword, used for swinging and striking, is significantly larger than a table knife, a tool for slicing food. And the table knife is larger than a craft knife, which is designed for precise cutting of paper in intricate shapes. Based on these observations, designers could identify what XR tasks they are intended for and select the optimal form accordingly.

6.3 Flexibility and Support

We noticed that the Long Stick, Standard Stick, and Thin Stick can lie along a spectrum of movement flexibility. The Long Stick, especially the Landed Stick form, offers the least flexibility, as it only relies on the user's elbow movements because the user's hands can only pivot around the point where the cane meets the ground. Without this constraint, the Standard Stick allows both elbow and wrist movements to be used. However, since the user has to hold the stick in their palm, they lose some finger flexibility. Thin sticks, which are a step further, can be maneuvered with the user's fingers. Consequently, it is the most flexible form and could be used in scenarios that require more diverse movements, such as simulating sculpting or medical operations in XR.

However, the Landed Stick does not sacrifice flexibility for nothing in return. It provides the user with arm support. A common issue in XR interaction is the "Gorilla Arm" effect, where the user accumulates arm fatigue due to holding the arm in the air over time. Providing *support* is a plausible solution to address this issue. Beyond reducing arm fatigue, providing support can potentially stabilize movements, which can lead to more accurate operation. For instance, P6 proposed to use a cane design to rotate and scan 3D environments stably. However, if the user needs to do more than pivoting around the cane's landing spot, such as with Lifted Stick, it will gain flexibility but cause more fatigue than short sticks due to its heavier weight.

On the other hand, the Standard and Thin Stick do not offer direct support when used in mid-air. However, they could potentially offer support to users in some circumstances with additional structure, like a table that supports users' arms when they write on the table with a pen. Designers could potentially design structures to offer support for Standard and Thin Sticks. For instance, researchers have proposed designs where a thin stick's tip is mounted to a robot-arm-like mechanical structure [1, 14, 19, 22], as shown in Figure 8-C.G1. Although such designs were intended for better tracking or providing haptic feedback, we feel this could also be providing support to a user's arm against gravity. However, when support is added, movements will be limited to some degree. When we draw on a table, it is a 2D platform on which the pen is moving. When we move with a robot arm, we only move where the arm

Table 2: Summary of the advantages and limitations of different forms.

	Hosting Inputs	Power and Precision	Flexibility	Support
Thin Stick	Provides **fewer opportunities** due to its size. Suitable for tab or squeeze interaction.	Provides **more precision**. Suitable for functions that require more precision, such as Surface Work and Pointing.	Provides the **most flexibility**. Allows elbow, wrist, and finger movements.	Provides no support unless designed intentionally.
Standard Stick	Provides **more opportunities** than Thin Stick. Can host more complicated controls like touchpads, thumbsticks, or sliders.	Between Thin Stick and Long Stick.	Less flexible than Thin Stick, but more flexible than Long Stick. Allows both elbow and wrist movements.	Provides no support unless designed intentionally.
Long Stick	Similar to Standard Stick.	Provides **more power**. Suitable for functions that require greater power, such as Moving, Deforming, Supporting, and Locomoting.	**Landed Stick**: Provides the **least flexibility** due to the orbiting movement around the pivot point. Allows elbow movement only; **Lifted Stick**: Provides better flexibility than the Landed Stick because it does not have the orbiting constraint. But it is less flexible than Standard Sticks when held with double hands.	**Landed Stick**: Provides arm support. Possibly able to **reduce fatigue and increase movement stability**; **Lifted Stick**: Provides no support and possibly the **most fatigue** due to its larger weight and dimension than Standard and Thin Sticks.

allows us to move, and there is more friction than usual. It would be ideal if we could find an ergonomic form that provides enough flexibility while supporting the user's arm when using the controller. In that regard, products like Armon Edero arm support [6] are good illustrations of balancing support and movement, allowing the user to move their arms naturally with little effort. We encourage future researchers to consider this direction.

7 DESIGN OPPORTUNITIES

In this section, we juxtaposed existing stick-based XR controllers in both industry and academia with the forms participants designed. This comparison aims to shed light on potential stick-based forms that remain unexplored within the realm of XR controller design (**RQ3**).

7.1 Existing XR Controllers with Proposed Forms

We collected 26 existing XR controller designs, including two commercially representative VR controllers from Meta Quest [5] and HTC Vive [35], four VR accessories to transform these commercial controllers into different forms, and twenty XR controller designs from prior work in academia. They fall into 5 different forms, as illustrated in Figure 8.

The most commonly adopted form is the Standard Stick form, where the user holds a short stick in the palm. Among these, the most popular is the **Thumb Out** variant (Figure 7-A.G1), where the thumb rests on the stick and manipulates primary controls. Both commercial controllers and 7 research prototypes [8, 18, 30, 34, 36, 38, 39] fall into this category. A significant focus within these research prototypes has been allocated to combining Weight Changing designs that aim to mimic the haptic feedback delivered by various VR objects [8, 18, 30, 34, 36, 39]. This aligns well with the A.V1 variation proposed by our participants (Figure 7-A.V1).

The Standard Stick's A.G2 gesture pattern, **Index Out** (Figure 7-A.G2), where the user rests their index finger on the device, is also a frequent choice [7, 9, 10, 17, 37, 40]. We noticed that researchers often employed this pattern to offer haptic feedback to the index finger so that the user could feel the shape or texture of virtual objects [7, 9, 37]. This approach aligns with everyday experiences, where the index finger is commonly used to explore objects instead of fingers like the thumb. This pattern can also be extended longer to where the index finger points, such as in [40], a white cane to help blind users experience VR. In this case, the stick functions as an extension of a user's index finger to feel the virtual world. Similarly, a "magic wand" proposed by Ciger et al. helps the user to point and interact with the digital world [10]. We also consider it the A.G2 form to extend a user's index finger on pointing.

It is also a prevalent design choice to adopt the **Thin Stick** form, where the user holds a thin stick and manipulates it as a pen (Figure 7-C.G1). This group of research heavily emphasizes precise interactions [1, 14, 16, 22, 23, 31]. For example, Pham and Stuerzlinger compared a pen-shaped controller with HTC Vive and a mouse on pointing tasks in XR [23]. They found that the pen-shaped interface significantly outperforms modern VR controllers (i.e., a Standard Stick form) and is comparable to a conventional mouse. The pen-shaped interface has also been used for AR surgery training that requires high precision [14].

Furthermore, some controllers require two hands to control one stick, akin to the **Long Stick - Double Hand** pattern we proposed (Figure 7-B2.G1). These mostly include commercial products to install to commercial VR controllers to simulate longer tools in games such as golf, saber, or gun [2–4]. It is worth mentioning that in the Haptic Links study [33], researchers employed a flexible link to connect two VR controllers in order to simulate different tools that require two hands to use.

Finally, we observed one instance of the **Landed Stick** form (one of the Long Stick forms, Figure 7-B1.G1), which is another accessory

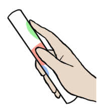
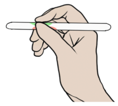
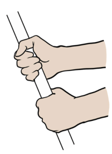
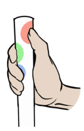
Form	Existing XR Controllers
 **A. Standard Stick - A.G1. Thumb Out**	• HaptiVec [8], • TORC [18], • Meta Quest Controller [20], • **Transcalibur [30]**, • **ElastOscillation [34]**, • HTC Vive Controller [35], • **VibroWeight [36]**, • DexController [38], • **Drag:On [39]** (The device with A.V1. Weight Changing design are in **bold**)
 **A. Standard Stick - A.G2. Index Out**	• NormalTouch and TextureTouch [7], • CLAW [9], • The Magic Wand [10], • Modified PHANToM haptic device (table tennis bats) [17], • Navigation cane controller [32], • Haptic Revolver [37]
 **C. Thin Stick - C.G1**	• **Modified PHANToM haptic devices [1], [14]**, • Arc-Type and Tilt-Type [16], • **The SmartTool [22]**, • A 3D pen-like device [23], • **The PHANToM haptic device [31]** (Thin Sticks attached to a mechanical structure are in **bold**)
 **B2. Lifted Stick - B2.G1 Double Hand**	• Amavasion VR Golf Club Handle [2], • HUIUKE VR Game Handle [3], • Magni Stock VR Stock Rifle Adapter [4], • Haptic Links [33]
 **B1. Landed Stick - B1.G1**	• FOX ONE VR Flight Stick [13]

Figure 8: Existing XR controllers with the proposed forms.

product for commercial controllers to simulate gear levers for flight games [13].

7.2 Unexplored Designs

Compared to the forms we proposed in Section 5, we identify the following opportunities in stick-based XR controller designs that remain unexamined. We also marked the underexplored design in Figure 7.

First of all, we think the **Landed Stick** (Figure 7-B1) holds big potential for XR TUI design. While certain controllers do exhibit a Long Stick form [10, 40], they are used for touching objects instead of providing support to the user. We rarely observe any existing XR controller design that has adopted the Landed Stick form. As discussed in Section 6.3, the Landed Stick, although it imposes limitations on a user's movement flexibility, may be able to relieve arm fatigue from holding the handheld XR device over time. Consequently, this might extend usage duration and promote greater movement stability. As to the movement limitation, it is worthwhile to consider the Flexible Support designs that we mentioned in the Function taxonomy (Section 4.1), which could offer both support and degree of freedom using certain mechanisms. Besides this, the Landed Stick also presents an opportunity to make XR content more accessible to users who face challenges standing or walking. It could also be repurposed as an AR hiking stick to furnish hikers with augmented information during their trips.

Secondly, although numerous studies have examined the use of pen-shaped interfaces in XR, all of these are held in the same way, with the user always using one of the tips for pointing in XR. Current research has yet to leverage the flexibility usage of **Thin Stick** (Figure 7-C.G2 and C.G3), as what P12 proposed, which is a Thin Stick could be manipulated between fingers to fulfill multiple gestures. Such design could benefit scenarios where the user needs tools for executing dynamic gestures and precise operations, such as when simulating medical instruments.

Another avenue to explore is the application of **Modular Design**. We presented two modular designs from Section 5: a Top-Middle-Bottom modular approach and a Building Block style design. These versatile designs could potentially be used in cases that necessitate the simulation of a variety of tools. Also, we feel the idea of modularity could be applied to combine multiple forms together, thus integrating the advantages of various forms. For example, we could design a cane interface with a thin stick as the top component so that it could both provide arm support and allow precise pointing.

Moreover, although many studies have delved into the Weight Changing design in XR controllers, we have yet to encounter work that incorporates a **Length Changing** design, as mentioned in Figure 7-B.V1. Similarly, the **Extensible Rope** concept (Figure 7-B.V2), as suggested by P8, is also unexamined. This would involve a soft and extendable component, such as a rope, at the end of the stick, thereby providing a distinct type of haptic feedback to the user.

8 LIMITATIONS AND FUTURE WORK

We identified two primary limitations of this work, which could point to future work. First, the potential forms we proposed fully rely on our participants' submissions. Given that we only engaged with 12 expert participants, and regulated the thinking time for experiment activities to maintain an appropriate duration, it is plausible that we might not have encapsulated all potential cases of stick-based objects' affordances and design opportunities. Future work could involve more expert participants, and allow more contemplation time for participants to reveal the depth and breadth of the ideas. Second, though our research questions focused on the preliminary conceptual foundations of stick-based XR TUI design, we did not demonstrate functional prototypes in this work, which limits the validity of the insights. In the future, we will develop and present functional prototypes based on the derived design opportunities.

9 CONCLUSION

In conclusion, this paper explored the use of stick-based design in XR UI design. By studying the affordances of daily stick-based objects via a participatory design session, we presented a taxonomy detailing stick-based objects' affordances in terms of functions and gestures. Following that, we proposed four stick-based XR controller forms, namely Standard Stick, Long Stick, Thin Stick, and Modular Design. Then, we discussed their advantages and limitations. In the end, we juxtaposed twenty-six existing stick-based XR controllers against our proposed forms and identified opportunities that remain unexamined yet for stick-based XR TUI design, including Landed Stick, Modular Design, the more flexible use of Thin Stick design, the Length Changing design and Extensible Rope design. Future designers interested in stick-based XR TUI design can refer to our findings to make informed decisions on selecting suitable forms that cater to their distinctive requirements.

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