CaneXR: Building a Cane-Based XR Controller for Knowledge Work

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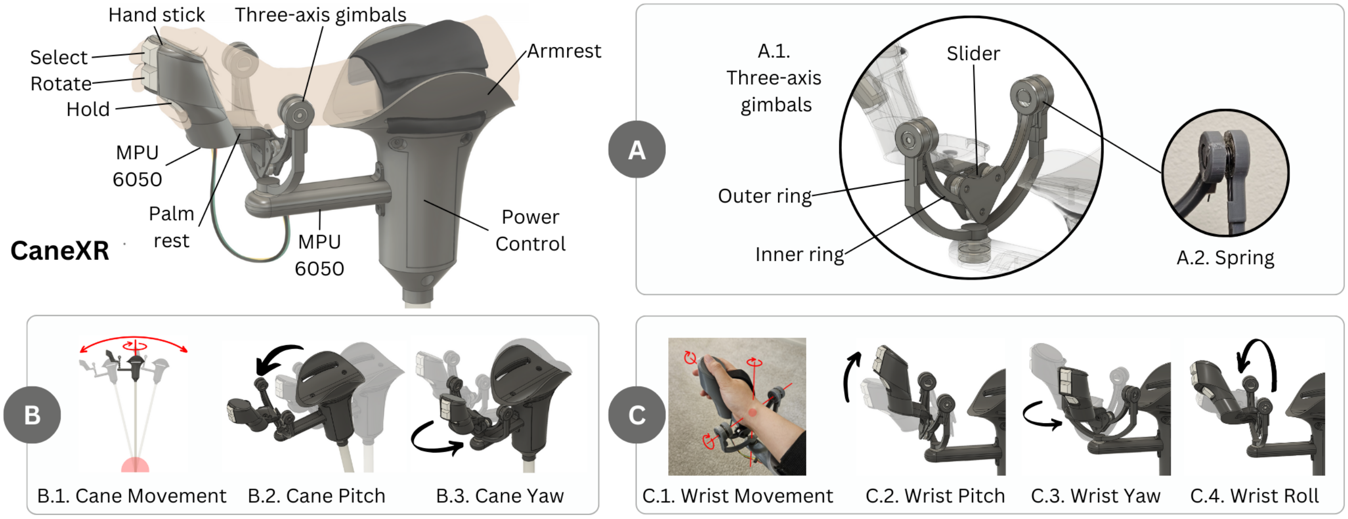

Figure 1: CaneXR: Cane-based XR controller with five degree-of-freedom (DOF) control designed for precision operations and fatigue mitigation. (A) The structure of the three-axis gimbal system with a spring solution to counterbalance gravity. (B) The cane supports 2-DOF movements. (C) The three-axis gimbal system supports 3-DOF movements with the wrist joint as the rotational center.

Abstract

While extended reality (XR) has gained traction in entertainment, its application in knowledge work remains limited. This is partially due to challenges of existing interaction methods on facilitating prolonged, high-precision operations without fatiguing the user. Previous research suggests that a "cane" shaped design may mitigate these issues by providing ergonomic arm support. However, designs exploring this configuration are lacking. We present CaneXR, a cane-based controller with ergonomic arm support that provides controls with five degrees of freedom and operates a 3D cursor in the 3D space for object manipulation. We conducted a pilot study on its usability and received positive feedback on the adoption of support. Based on the results, we presented improvement opportunities to iterate on this prototype and expand its supporting features.

CCS Concepts

• **Human-centered computing** → **Interaction devices**; **Virtual reality**; **Mixed / augmented reality**.

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Keywords

Tangible User Interface, Extended Reality, Cane Stick, Device Form Factor, Handheld Device, Ergonomic, Dynamic Arm Support, Knowledge Work

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1 Introduction

The application of extended reality (XR) technology to knowledge work has gained increased attention due to its potential advantages as an immersive media that brings an enhanced feeling of presence, infinite display space, and improved 3D perception [6, 27, 40, 49]. Knowledge work often requires prolonged high-precision operations [56]. However, most existing XR interfaces require the user to conduct mid-air interactions with bare hands or handheld controllers. For an extended period of time, mid-air interactions can cause arm fatigue and discomfort [18, 25], an effect known as the "gorilla arm" [24], which hinders precise and comfortable input for knowledge work.

Researchers have proposed different solutions to prevent users from experiencing the gorilla arm syndrome. One solution with high potential is adopting traditional desktop input such as mouse and keyboard into XR applications [21, 22, 41, 56]. However, this approach restricts users to the desk area, partially negating the advantage of XR providing an infinite immersive space. Another potential solution is to decouple the motor space from the visual space [6], such as when operating virtual content with a tablet at hand [32] or redirecting ray casting [2]. However, this approach only alleviates the chances and effort of raising hands. The user would still need to hold the input device for prolonged use, especially in tasks requiring accuracy and precision. A new study on novel handheld devices for XR has identified the "cane" form as an unexplored but highly promising form for XR controllers [53]. This form offers arm support, potentially reducing fatigue but improving operational precision. However, a key challenge lies in balancing the need for arm support with the need to allow sufficient movement flexibility for instructing operations in XR.

In our work, we proposed a novel cane-based XR controller, **CaneXR** (see Figure 1), with ergonomic arm support that provides a five degree of freedom (DoF) control and operates a 3D cursor in the 3D space to manipulate objects. We detail the implementation of the tangible interface design and the interaction design in Section 3. Additionally, we conducted a qualitative pilot study with four XR experts and gained positive comments on CaneXR's ergonomic supports on precision interaction and their effect on fatigue alleviation (see Section 4). We also identify areas for improvement and put forth future plans based on our findings.

2 Related Work

2.1 XR for Knowledge Work

Knowledge work is a concept first introduced by Peter Drucker [14] and refers to activities that require information workers to apply theoretical and analytical knowledge to develop products and services. XR, as an immersive interactive media, brings several advantages to knowledge work. It enhances the sense of presence in remote collaboration [6, 13, 16, 36, 42, 44] and provides infinite display space and richer 3D visualization that facilitates data visualization and analysis [7, 9, 11, 19, 23, 34, 37, 38, 49, 54, 57]. It also strengthens 3D perception [27, 40], which is especially valuable for 3D modeling work such as product design [26, 33, 51], urban planning and architecture [49], etc. One of the challenges of adopting XR for knowledge work lies in facilitating precise and comfortable input, particularly for prolonged usage [56]. This is due to the fatigue that may arise from interacting with elevated content in an infinite 3D space via spatial, mid-air interactions [6, 52]. One solution is adopting input remapping [6], which allows the user to manipulate harder-to-reach content by alternative operations—e.g., using a handheld tablet [32] or employing a virtual pad that redirects laser cast input to higher content [2]. Yet, prolonged holding of the input device without a stable supporting platform remains an issue. Another solution is to utilize a traditional desktop mouse-keyboard setup for XR virtual content interaction [21, 22, 41, 56]. This not only facilitates high operation precision with users' arms resting on the table, but also lowers the learning cost for users transitioning from desktop applications to XR. However, the use of these desktop accessories restricts users to the desk area, which conflicts with the central feature of XR, which is to provide an infinite immersive space with a high degree of movement.

Our work proposes a novel angle to this challenge: using a cane to provide ergonomic continuous support and mobility at the same time. In contrast to the solutions described earlier, we present a new perspective for addressing this challenge by employing a cane-based controller, and as Figure 1 shows, it offers XR users both ergonomic support and mobility simultaneously.

2.2 Ergonomic Arm Support Designs

Ergonomic arm supports can potentially minimize exertion during arm movement and alleviate arm fatigue. For instance, Tapanya et al. [47] assessed an ergonomic prototype for upper arm support during smartphone use and found that arm support can significantly reduce the activities of arm muscles, thereby reducing fatigue [47]. Ergonomic arm supports have been integrated into many daily products, especially for aiding muscle weakness [4, 29], mobility issues [15, 17], or work fatigue [8]. Such devices typically feature a curved platform that hugs the user's forearm, potentially combined with a grip handle to move the device. For example, some walkers have employed this design to allow users to rest their arms while pushing the walker forward [15]. Our CaneXR is inspired by such a design. The type of ergonomic arm support that permits movement is called Dynamic Arm Support [12]. They employ various mechanisms including *non-actuated devices*, which need the user's strength to drive movements [8, 30]; *passively actuated devices*, which utilize mechanisms such as counterweights, springs, or elastic bands to counter the gravitational pull on the arm [1, 28]; and *actively actuated devices* incorporate external pneumatic, electric, or hybrid energy sources to provide greater forces and more precise movement control [5, 20]. CaneXR's design is passively actuated in that we adopted a spring solution to counterbalance gravity. Our work distinguishes it from existing ergonomic arm support devices as an active controller. It utilizes support not simply to minimize muscle fatigue but also to leverage user movement while leaning and pivoting on the support as input to control digital data in XR applications. To our knowledge, there is no existing controller design that employs ergonomic arm support as its input mechanism for XR systems.

2.3 Cane-based Handheld Devices

Existing cane-based handheld devices are mainly designed for blind and low vision (BLV) users. One primary category is "smart canes" for BLV users to enhance their abilities to understand and navigate through their surroundings. Such design typically includes one or more sensors such as ultrasound sensors [35, 48, 50], inferred sensors [35], water sensors [3, 35], or cameras [10, 31] to detect the environment. Upon identifying noteworthy situations, they alert users via handle vibrations [10, 31, 35, 45, 46], buzzer warnings [3], or voice messages [10, 35, 50]. These smart canes function by providing signals to the user. One notable example is GesturePod, a cane that can act as an input device for white cane users and can register gestures such as tapping, twisting, twirling, and swiping to control digital devices [39]. While this work is closer to our prototype, there are some notable differences because we used the cane as an instrument to perform hand movements and control 3D cursor operations specific to XR environments (more on its features in section 3). Besides those smart canes to help detect the users' surroundings, Microsoft Research proposed cane-based devices to simulate a virtual environment for BLV users with haptic and audio feedback [43, 55], which is the only cane-based XR controller we have noticed. However, all of these existing cane-based controllers function as detectors rather than supporters. The user is required to lift the cane in order to use them. In contrast, our work aims to allow the user to rest on the cane on the floor and perform precise and extended operations over long periods of time. To the best of our knowledge, we have not come across a handheld cane-based device that serves this specific dual purpose of providing continuous resting support and enabling interactions with virtual objects.

3 CaneXR Prototype Design

We propose CaneXR, a cane-based controller that provides 5-DoF movement for the user to control a 3D cursor to manipulate virtual objects in XR environments. We utilized Fusion 360 to create a 3D model of the prototype, followed by 3D printing the components using PLA plastic. The various parts were then assembled using mainly screws. Please refer to the supplementary video included with this paper to see how the prototype and the interactions with it work.

3.1 Tangible Interface Design: Five-DoF Dynamic Support

In this section, we detail the hardware design of the CaneXR controller (see Figure 1). The core structure of CaneXR draws inspiration from established ergonomic support devices, such as forearm crutches and arm supports described in the previous section. The physical design of the CaneXR comprises three main components: 1) a cane stick equipped with an armrest, 2) a three-axis gimbal system facilitating wrist movement, and 3) a hand stick with a palm rest.

3.1.1 Cane Stick with Arm Rest. The cane stick serves as the primary support for the user's arm, providing stability from the ground up. At the top of the cane stick, an armrest platform allows the user to rest their arm comfortably. A strap can be utilized to securely bind the user's arm to the cane, enabling them to lift the cane with one hand. While supporting the weight of the user's arm, the cane stick offers two degrees of freedom: forward-backward movement (pitch) and left-right rotation (yaw) (see Figure 1-B). Although users can theoretically conduct roll rotation by moving their arms closer to or farther from their torso (abduction/adduction of the shoulder joint)—akin to the motion of a "chicken dance"—this movement is excluded due to its limited range and reduced comfort compared to the primary motions. Beneath the armrest, a chamber houses the power control inside, with a case for a 5-volt 18650 rechargeable battery. The power switch and indicator light are located on the exterior of the chamber. Near the top of the cane stick, a horizontal bar extends outward, to which an inertial measurement unit (IMU) sensor, MPU6050, is affixed underneath to monitor arm rotation. This structure connects to the three-axis gimbal system.

3.1.2 Three-Axis Gimbal System. A gimbal is a pivoted support that permits the rotation of an object about an axis. The three-axis gimbal system consists of an outer ring, an inner ring, and a slider on the inner ring (Figure 1-A). It provides three DOF for movement in pitch, yaw, and roll (Figure 1-C), with the user's wrist joint as the rotational center (Figure 1-C.1). The outer ring has a pin at the bottom that connects to the horizontal bar through a 608 bearing, facilitating yaw rotation. The outer ring also includes two 607 bearings at each end, which connect to the two 607 bearings on each end of the inner ring to enable pitch rotation. The inner ring, shaped like a half circle, has grooves on both its inner and outer sides, creating a rail for the slider to traverse in the roll direction. The slider contains three 605 bearings, with two moving along the inner groove of the ring and one along the outer groove. Two triangular shells at the front and back secure the three bearings in place with three pins. The slider incorporates an L-shaped connector to attach to the palm rest of the hand stick.

One challenge we faced was that the weight center of the hand was not at the joint center of the wrist. Consequently, gravity tends to pull the user's hand downward in the pitch direction, resulting in increased effort to keep the hand straight. There are multiple potential solutions, including modifying the size and weight center of the hand stick or the gimbals to counterbalance the weight of the hand, or involving vector control motors to regulate torque on the gimbals precisely. Ultimately, we adopted a simple spring solution to counteract the effects of gravity (Figure 1-A.2). On each end of the gimbal rings, where the inner ring connects to the outer ring, we installed a 60° torsion spring to apply outward pressure between the two rings. We selected the specifications of the springs to provide approximately 400 grams of lift—the average weight of an adult's hand—when the springs are compressed to a 0° position. This approach effectively allows the user's hand to rest naturally in an upright position.

3.1.3 Hand Stick with Palm Rest. The hand stick features a palm rest at its base, which connects to the slider of the gimbal system, allowing the user to rest their hand while gripping the hand stick. We let the stick tilt forward at an angle of 24° to enhance user comfort (Figure 1). The chosen tilting degree was the most comfortable one after trying multiple 3D-printed prototypes. The stick was equipped with three buttons: two smaller buttons designed to be pressed by the user's index and middle fingers and a larger button positioned below to be pressed by the ring and pinky fingers, as can be seen from Figures 1 and 2. From top to bottom, we refer to them as the Select, Rotate, and Hold buttons and will explain their use in Section 3.2 soon. To facilitate movement of the hand stick without the risk of accidentally pressing the buttons, a strap securely binds the stick to the user's palm. A second MPU6050 IMU sensor is mounted at the bottom of the hand stick to detect wrist rotation. Inside the hand stick, an ESP-WROOM-32 microcontroller module is integrated, responsible for transmitting the status of the three buttons and the two IMU sensors to the XR application via WiFi using User Datagram Protocol (UDP).

3.2 Interaction Design: 3D Cursor

3.2.1 3D Cursor. CaneXR controller possesses the advantage of allowing the user to conduct micro-movements while resting their hand. As a result, common XR interactions such as a 1:1 mapped virtual hand or laser pointing are not suitable due to their requirement of significant hand movements. To meet our needs, we developed a 3D cursor interaction extending from the traditional mouse-controlled 2D cursor system in desktop applications. The 3D cursor, represented as a floating arrowhead in the virtual space, is maneuvered through the user's elbow and wrist movement on the CaneXR controller. Besides allowing micro-movements for control, the 3D cursor also possesses three benefits. First, it effectively navigates complex 3D scenes where objects may overlap or obscure one another, a capability laser casting lacks. Second, its sharp tip provides superior precision for object selection compared to virtual hands. Finally, the 3D cursor's design aligns with familiar desktop software solutions, making it more intuitive for knowledge workers.

3.2.2 Cursor Movement and Coordination System. We implemented a clutch mechanism to decouple hand and cursor movements, akin to a 2D mouse cursor–it follows the hand movement when the mouse is held against the table and stays still when the user releases or lifts the mouse. CaneXR users can only move our 3D cursor when "holding" the hand stick tighter, i.e., by pressing down the **Hold button**. The cursor remains stationary when the user disengages the Hold button, thus allowing the user to adjust their hand pose without affecting the cursor's position. Once pressing and holding the Hold button, the user can manipulate the cursor position through specific hand movements (see Figure 2-A). The user can swing their arm or hand left or right on the yaw axis to adjust the cursor's x position. The hand rotation has a smaller control-display ratio (CD ratio) than the arm for more precise operations. The user can combine both arm and hand moves for compound adjustments. For modifying the cursor's y position, the user can tilt the hand up or down on the pitch axis. Similarly, the user can tilt the cane forward or backward to alter the cursor's z position.

Since the user can locomote in the 3D space, the cursor's moving directions adapt to the user's orientation. Each time when the Hold button is engaged, the cursor's coordination system recalibrates: the forward direction aligns to the direction where the user's center eye direction is projected to the horizontal plane. The up direction remains vertical, while the right direction is perpendicular to the forward and up directions.

3.2.3 Object Manipulation. We designed our interaction to fulfill common CAD tasks of hovering, selecting, moving, and rotating. When the cursor's tip contacts a manipulatable object, the object enters into a "hover" state, indicating its readiness for selection. Then the user can press the Select button to select it or move the cursor away to cancel the hovering (Figure 2-B). Once an object is selected, the user can either dismiss the selection by clicking on an empty space or manipulate the selected object's position and rotation in two ways. The first way is **gizmo manipulation**. Upon selecting an object, a gizmo appears, featuring three positional handles and three rotational handles (Figure 2-B). The user can drag these handles (by hovering on the handle and holding the Select button while moving the cursor) (Figure 2-D) to translate or rotate in the corresponding direction. The second method, **free manipulation** (Figure 2-C), triggered by the user hovering on the selected object and then holding either the Select or Rotate button, allows the user to directly translate or rotate the object. The user can hold the Select button while moving the cursor to let the object follow the cursor's position. Alternatively, they can hold the Rotate button while rotating their wrist. When rotating, the cursor movement is paused, and the user's wrist rotation delta will be applied to the object.

4 Pilot Study

To preliminarily understand the usability of our prototype, we conducted a qualitative pilot study with four participants (P0 - P3, 3m/1f, age 25 - 27, all experienced with XR technologies and HCI research).

The pilot study lasted for approximately 30 minutes for each participant. In the first 15 minutes, we allowed participants to engage in 2D CAD operations using a mouse and keyboard, letting them recognize the limitations of the 2D interface in terms of 3D modeling, specifically the absence of depth perception. Then, we let the participant experience the same CAD operations in VR with a Quest Pro headset and its associated controllers. Subsequently, we explained the fatigue issue caused by long usage and presented the CaneXR controller to the participants. Unfortunately, due to sensor issues at the time of the study, we were unable to provide real-time testing of the interaction. Instead, we played a recorded demonstration video displaying both the user's movement and the view in VR (as attached in the supplementary material) that showcased manipulating the cursor and objects with the CaneXR controller. While watching, the participant shadowed the movement with the CaneXR controller as shown in the video, engaging in a "Wizard-of-Oz" scenario. With this approach, the participants were able to sense the interaction.

For the second half of the study, we interviewed participants about their opinions on the CaneXR prototype. Our questions focused on two aspects: the tangible interface design (hardware) and

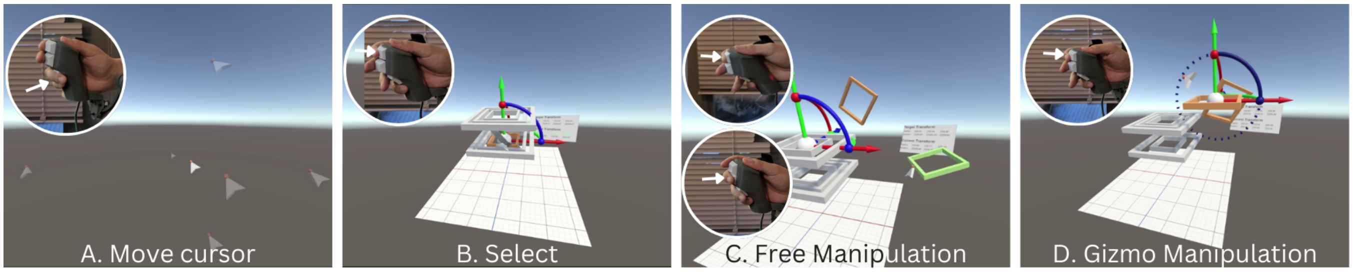

Figure 2: CaneXR Interactions in an XR environment: (A) moving the 3D cursor with the Hold button, (B) selecting an object, (C) manipulating an object in 6-DOF (free manipulation), and (D) manipulating an object in 1-DOF (gizmo manipulation).

the interaction design (software). Regarding the tangible interface design, we first asked the participants to provide their overall feedback while holding and moving with the controller. Then, we asked their opinions on the armrest, the gimbal system, and the hand stick, respectively. For the interaction design, we again asked for overall comments first, followed by specific inquiries on the cursor moving and the object manipulation. The experimenter asked follow-up questions when needed. When an interesting discussion appeared, we sought opinions from subsequent participants.

To analyze the data, we first did an open coding process across the recordings sentence by sentence and marked the key opinions for each sentence. We then conducted axial coding by grouping participants' opinions into three themes (support, fatigue, and precision) and six aspects (button, hand stick, wrist, elbow, straps, and interaction). We were especially interested in these themes and aspects to further iterate the prototype. Within each aspect and theme, we compared and concluded participants' opinions.

5 Results and Discussion

5.1 Support may reduce fatigue with some constrained feeling

Providing support is the key objective of our CaneXR design. We gladly observed that participants mainly hold positive opinions on the support design. In terms of fatigue, most participants agreed that the support design could reduce fatigue. P0 mentioned *"[CaneXR] solved the sore arm problem. It's indeed hard to feel fatigued if I put my arm and hand on it."* P1 stated, *"CaneXR provided a point of support, which saves effort in long-term use."* P2 commented, *"[With CaneXR] I felt less burden because there's support."* However, participants expressed this support somewhat constrains their movement. P1 thought CaneXR's support and strap design were somewhat troublesome, and limited his movements to some degree. P2 expressed that CaneXR gave more *"feeling of constraints."* P3 even found the arm restriction uncomfortable, preventing her from prolonged use: *"[The arm support is] too restricting. I'd like to move freely and get my arm straight when I want. This [design] made my [elbow] joint hurt."*

5.2 Support may increase precision, but movement mapping requires improvement

In terms of precision, most participants predict that the CaneXR interface might offer improved precision due to the added support. P1 remarked, *"When I play VR shooting games, I've always wished to add support to the controller. So having something to rest on would definitely help with high-precision operations."* P3 provided another example regarding the application of eyeliner, where it can be challenging to achieve the desired contouring on the eyelids. P3 mentioned that experienced people often rest their hands against their cheekbones for stability during this process. However, P3 felt hand support would be sufficient for precise operations, and the elbow support was unnecessary. P2 also felt CaneXR could provide better precision: *"The precision winner must be the CaneXR [comparing to Quest controller]."* Moreover, he noted that the passive haptic feedback that the support increased his awareness of his hand position: *"The support has an 'anchored' feeling? Yea, I can also better determine the position of my hand."*

Designing an effective control-display mapping could be crucial for achieving operational precision. One challenge in our interaction is that we have to map the *rotation* of the arm/hand to the *position* of the cursor, which may not be as intuitive as other control methods, such as a desktop mouse, where the hand's x-y position directly maps to the cursor's x-y position, or the Quest controller, where the virtual controller tracks the real controller with exactitude. For the pilot study, we implemented a 1-degree-to-1-centimeter mapping ratio for cursor control, whereby each degree of axis rotation from hand or arm input triggers a cursor movement of one-centimeter distance in the corresponding direction. With this ratio, P0 felt the cursor in CaneXR moved faster than anticipated, whereas the Quest controller behaved more closely with user expectations. We could adjust the cursor to move slower, but it would be harder for the user to control the cursor for long distances. To resolve this, we could apply a dynamic mapping ratio in future iterations to make the cursor move slower when the user's hand moves slower, and vice versa—a trick desktop mouse does.

5.3 Challenges for button design

P2 and P3 felt the button positions were not comfortable enough to use, specifically noting that they had to exert extra effort to move their index and middle fingers upward to reach them. In contrast, P0 and P1 did not raise this concern. We felt it could be a challenge to accommodate varying hand sizes. Users with smaller hands might need to lift their fingers to reach the buttons. Conversely, lowering the button positions could prompt users with larger hands to lower their fingers, potentially causing them to squeeze their palms against the rest. P0 also expressed concerns about the Hold button being operated by the least frequently used fingers (the ring and pinky fingers), potentially leading to discomfort. Another refinement opportunity is the choice of button types. Our prototype currently features blue mechanical key switches, known for their clicky sound and crisp haptic feedback, but require more actuation force. However, P1, P2, and P3 all preferred a linear switch over the clicky switch. P1 said, *“I don’t like to use it [the clicky keys] for a long time.”* Compared to those on conventional keyboards, our buttons are harder to press due to the vertical orientation of our controller, which prevents users from leveraging gravity when pressing keys. Besides, P3 suggested making the button smooth and making the pressure detectable: *“I can micro-control the degree of pressing - pressing lightly or hard... When I press a little, it moves little; When I press hard, it moves big.”* Based on this feedback, we might consider switching to lighter, linear key switches like red switches, except for the Hold button. P1 and P2 felt the Hold button could remain clicky. P1 said, *“For game controllers’ [trigger] buttons, I usually don’t want them to be clicky. But we are making it behave like a mouse, so I hope the Hold button has a clicky feeling because their function is different.”* P2 said, *“Because the Hold button needs to give the feedback of zero or one—I need to know whether I pressed it.”* According to this feedback, we consider redesigning the Hold button to use the thumb with it instead of the ring and pinky finger. For the button type, we consider using a linear button for the Select and Rotate buttons and keeping a clicky button for the Hold button.

5.4 Reconsideration of resting hand pose

For our prototype, the resting hand is positioned vertically, with the palm facing left and the ulnar side facing down. P0 felt that moving the cursor up and down felt uncomfortable because it required the hand’s radial and ulnar deviation, which is not as comfortable as flexion and extension. He suggested making it horizontal, where the palm faces down, and the ulnar side faces right. We sought opinions from other participants but received varied feedback. P1 favored the horizontal position because *“it felt more like holding a mouse.”* But P2 felt horizontal is *“more comfortable because the palm rest is down there.”* P3 initially preferred vertical because *‘‘horizontal] felt weird,”* but she also acknowledged the horizontal pose’s advantage of resembling a mouse. For our future iterations, we will explore the horizontal resting hand pose and compare it against the current vertical pose.

6 Limitations and Future Work

This work has two limitations. First, we only asked a limited number of participants with past XR and HCI experiences to provide feedback on CaneXR in the pilot study. Although this is cost-effective for collecting professional opinions, we plan to extend the study further by inviting more participants with different backgrounds to share their feedback. Second, the pilot study followed the Wizard-of-Oz approach to receive preliminary feedback on CaneXR, rather than having participants experience using the prototype for real object manipulation. In the future, we plan to implement and iterate functional prototypes based on the pilot results. We will conduct lab experiments to examine the interface’s effect on fatigue and precision for XR operations in knowledge work and compare it with controller- and mouse-based interactions.

7 Conclusion

This paper presented CaneXR, a novel cane-based controller that provides arm support and five DOFs for arm movement to control a 3D cursor in XR. We detailed the implementation of the tangible interface design and the interaction design. Our pilot study showed the potential of the arm support design to reduce fatigue and increase precision, but it had some limitations, such as a sense of constrained and unexpected movement mapping. We hope CaneXR can inspire HCI and XR researchers to prototype cane-based interfaces and design novel interactions to support knowledge work in the future.

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