Investigating Wrist Deflection Scrolling Techniques for Extended Reality

Jacqui Fashimpaur
jacquiwithaq@meta.com
Meta Inc., Reality Labs Research
Redmond, Washington, USA

Amy Karlson
akkarlson@meta.com
Meta Inc., Reality Labs Research
Redmond, Washington, USA

Tanya R. Jonker
tanya.jonker@meta.com
Meta Inc., Reality Labs Research
Redmond, Washington, USA

Hrvoje Benko
benko@meta.com
Meta Inc., Reality Labs Research
Redmond, Washington, USA

Aakar Gupta
aakar.hci@gmail.com
Meta Inc., Reality Labs Research
Redmond, Washington, USA

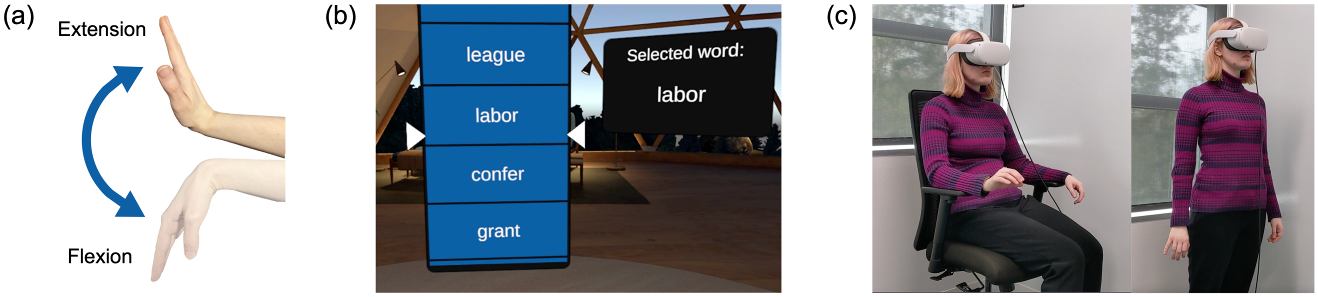

Figure 1: (a) Flexion and Extension, which is one of the axes of wrist deflection. This is the primary input to our scrolling techniques. (b) An example XR interface that supports scrolling and selection, used in our study to teach participants the scrolling techniques. (c) Two postures in which we evaluated our scrolling techniques, arm-in-front and arm-at-side.

ABSTRACT

Scrolling in extended reality (XR) is currently performed using handheld controllers or vision-based arm-in-front gestures, which have the limitations of encumbering the user's hands or requiring a specific arm posture, respectively. To address these limitations, we investigate freehand, posture-independent scrolling driven by wrist deflection. We propose two novel techniques: Wrist Joystick, which uses rate control, and Wrist Drag, which uses position control. In an empirical study of a rapid item acquisition task and a casual browsing task, both Wrist Drag and Wrist Joystick performed on par with a comparable state-of-the-art technique on one of the two tasks. Further, using a relaxed arm-at-side posture, participants retained their arm-in-front performance for both wrist techniques. Finally, we analyze behavioral and ergonomic data to provide design insights for wrist deflection scrolling. Our results demonstrate that wrist deflection provides a promising method for performant scrolling controls while offering additional benefits over existing XR interaction techniques.

CCS CONCEPTS

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

KEYWORDS

scrolling, wrist deflection, freehand, wristband, extended reality, virtual reality, position control, rate control, user study

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1 INTRODUCTION

Scrolling is an essential form of digital interaction. In XR (an umbrella term for virtual, augmented, and mixed reality), scrolling is often performed using joysticks or touchpads on controllers or mid-air gestures that are detected by hand tracking via cameras on the headset [22, 32, 38]. Common mid-air scrolling techniques include touching and dragging the virtual content directly (as if it were a touch-screen) or raycasting towards the UI and holding a pinch gesture to drag the content at the point of intersection. These

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techniques can be effective but they each suffer from at least one of the following problems:

1. *Encumbrance.* Techniques that require users to carry physical controllers are impractical in some situations (e.g., running errands wearing an all-day XR device) and there are tasks where it is important for the user's hands not to be occupied (e.g., using XR to assist with assembling something).
2. *Constrained Arm Posture.* Sensing capabilities and interaction designs can both introduce constraints on the user's arm posture. For example, hand-tracking cameras are sensitive to occlusion, while techniques that involve raycasting towards or touching a virtual interface are sensitive to the interface's location, distance, and size. Techniques that require a specific arm posture are limited to contexts where that position is possible: one may not be able to e.g. hang their arm by their side when seated or outstretch their arm in a crowded space. Additionally, techniques that require users to hold their arms in front of them can be fatiguing during lengthy interaction sessions[11, 20], and are socially unacceptable in many contexts [42].

These issues often present a trade-off for XR interactions: users can either hold a device and provide input to any interface in any arm posture, or use freehand interactions and introduce posture constraints. To advance adoption of XR and applications to a broader range of tasks and contexts, there is a need for XR interaction techniques that are both freehand and arm-posture independent. A scrolling technique with these properties could enable users to e.g. navigate a grocery list while shopping, or choose from a few music options while walking, with ease and minimal interference with their primary task.

One promising solution could be to drive interactions with wrist deflection, the angle between one's hand and their forearm. This value is independent of one's arm posture, and wrist-worn optical sensors have shown to be a practical way to measure it without encumbering one's hands [15, 16, 44], so this presents an attractive and yet unexplored solution for scrolling controls and XR input in general. In fact, overall, scrolling in extended reality has not received much attention in the literature. As such, in the present work, we explore the design of XR scrolling techniques driven by wrist deflection.

We propose two novel scrolling techniques (i.e., Wrist Joystick that uses rate control and Wrist Drag that uses position control) and assess their viability, relative strengths, and ergonomic properties. In a user study with 24 participants, we compared the two wrist techniques with each other and with state-of-the-art analogs (i.e., Controller Joystick and Arm Drag) on task performance and user behavior. The wrist techniques were evaluated in two different postures: seated with one's arm on an armrest and standing with one's arm by their side.

The results indicated that neither wrist technique was strictly better than the other: participants were able to perform a continual browsing task more efficiently using Wrist Joystick, whereas they could perform a rapid target acquisition task more efficiently using Wrist Drag. Both techniques performed comparably to their state-of-the-art counterpart on their better task using an arm-in-front posture, and this performance was retained when participants transferred to an arm-at-side posture. These results support the idea that wrist deflection could enable effective freehand and posture-independent scrolling for XR. Furthermore, our analyses of behavioral and ergonomic metrics offer design insights for future development of wrist deflection interactions.

Thus this paper contributes:

- Two novel wrist deflection scrolling techniques, one based on rate control and another based on position control.
- An investigation comparing the two techniques with each other and with two state-of-the-art XR scrolling techniques, which demonstrated the viability of both wrist techniques while highlighting their relative strengths and weaknesses.
- Design insights for wrist deflection interactions based on behavioral analyses.

Posture-independent wrist deflection, sensed by a wristband, could present a practical solution to achieve flexible freehand XR input. Our work lays the foundation for this by showing its efficacy for scrolling interactions and revealing behavior patterns that are specific to this form of input.

2 RELATED WORK

This research was informed by prior research in the areas of scrolling interaction design, freehand input, and wrist angle input. Also of relevance is literature related to interactions with properties similar to scrolling, such as position and rate control transfer functions.

2.1 Scrolling Interaction Design

Scrolling behaviour modeling and scrolling technique development has been an important and well studied topic for computers and hand-held devices [2, 21, 33, 36, 41, 50, 57]. In these literatures, most continuous scrolling techniques use either "rate control" or "position control." With rate control, the user's input directly indicates the desired scrolling velocity. For example, a list might scroll faster the more a joystick is tilted in the corresponding direction. This type of control can be low-effort in that it allows content to scroll continuously without additional user movement, but it can make precise targeting difficult [6, 27, 48]. It is well suited to isometric devices with self-centering mechanisms, and suffers significant performance decreases without them [8, 56].

In contrast, position control enables the user to directly control the scroll position. For example, dragging a finger across a touch screen might move scrollable content to a new position whose offset is the same as the finger's. Mouse scroll wheels and touchpads also fall into this category. In general, position-controlled scrolling techniques have been found to provide users with precise control of scrollable content, but they often require "clutching" [34, 57], where the user must disengage from position control (such as by lifting their finger), reset their position, and re-engage to keep scrolling in the same direction. Touchscreens and touchpads often reduce the need for clutching by supporting flick interactions, in which scrollable content behaves like an object with momentum and can be "thrown" some distance using a quick drag and release [1, 12, 39].

Most common scrolling techniques fit into one of these two categories, but others have been proposed, such as "inertial control," where the scrollable content behaves as if it has momentum and is sliding on a surface being tilted by the user [35, 53]. In extended reality, some commercial controllers have joysticks for rate-controlled scrolling (e.g., Meta Quest Touch Controllers [38]), while others have touchpads for position-controlled scrolling (e.g., HTC Vive Controllers [22]). These devices encumber the user's hand(s), making them impractical or inconvenient for portable use, and motivating freehand alternatives.

2.2 Freehand Scrolling

Though several techniques have been proposed for mid-air freehand pointing and selection [19, 23, 51], or discrete command gesture detection [5, 31], research specifically investigating freehand scrolling is sparse. Boundless Scroll [47] used a tracking system around a touchscreen to enable users to continue dragging after their finger left the edge of a device, however it specifically targeted touchscreen devices and does not necessarily extend to XR scrolling.

Many XR devices support freehand interactions using cameras contained in the headset and computer vision algorithms. A common approach to scrolling with these systems is to use freehand pointing interaction (i.e., a ray cast out from the user's hand onto a virtual interface) in combination with a sustained pinch to "grab," "drag", and "throw" scrollable content. Such vision-based techniques are convenient in that they require no additional devices aside from a headset, but they are sensitive to lighting conditions and occlusion. Additionally, they require a user to hold their arm out in front of them. This is not only conspicuous [42] but also fatiguing [11], with extended use leading to the "gorilla arm effect" [20].

To counter these challenges, some researchers have proposed methods for freehand arm-at-side input; however, to date, none of these have been evaluated for scrolling interaction. Gunslinger [30], for example, used 3D cameras mounted on both thighs to track hand poses, and had a vocabulary of gestures for two-handed interaction with a wall display. WatchTrace [45] used a smartwatch's gravity sensor data to detect arm-at-side arm gestures. These techniques, while useful, were limited to standing, arm-at-side postures (though Gunslinger supported simultaneous touch interaction). ARPads [4] experimented with multiple arm positions for indirect pointing in AR, but each position required a different 3D camera placement and had a different virtual target plane, as opposed to a single technique being posture-independent. Gestures involving one's 3D hand pose [26] could be detected in any arm posture, but presented a much harder tracking problem than detecting the angle of the wrist, without necessarily providing any added value for scrolling. Our work demonstrates that wrist deflection is sufficient to drive effective freehand scrolling.

2.3 Wrist Angle Input

The wrist is a dexterous joint that can rotate on the axis of the forearm (i.e., pronation/supination), on the axis pointing out of the palm (i.e., radial deviation/ulnar deviation), and on the axis perpendicular to those (i.e., flexion/extension, Fig. 1a). Extensive research has demonstrated the expressiveness of wrist angles as a form of input [12, 16, 18, 35, 40, 49, 52]. Rahman et al. [40], for example, found that users could comfortably control their flexion/extension with a precision of roughly 5°. Tsandilas et al. [49] argued that the wrist can be viewed as isotonic around its neutral position and elastic when deflected past a certain range.

To capitalize on the flexibility of the wrist, some have proposed using the reorientation of handheld devices as a proxy for wrist input. For example, device tilting has been explored for text entry [54], pointing [48, 49, 53], and scrolling [12, 35, 36, 41]. These methods have proved compelling, but they occupied the user's hand. Smartwatches [10, 17] and rings [18] are alternatives for tilt-based interaction using built-in gravity sensors. However, all of these tilting techniques rely on an object's orientation relative to a user's environment rather than relative to the user's forearm, which means the user must constrain their orientation. Wrist deflection input, as considered in the present research, circumvents this challenge and allows users to flexibly transition between any arm posture.

Several sensing techniques have been proposed to detect wrist deflection, including multiple IMUs [55], magnetic sensors [52], stretch sensors [46], and optical sensors [15, 16, 44]. RotoWrist [44] specifically demonstrated continuous wrist deflection estimation using optical time-of-flight sensors. The same apparatus and approach was used to estimate wrist angles for our techniques. These prior works demonstrate the potential of wrist deflection sensing for wristband devices, but did not investigate scrolling input. Fukui et al's [13] work compared several arm-in-front scrolling techniques that were driven by forearm pronation and supination rather than deflection. Our work investigates flexion-extension wrist angles for both arm-in-front and arm-at-side postures for extended reality use cases.

3 PROPOSED TECHNIQUE DESIGNS

We implemented several prototype scrolling techniques, iterating separately on rate control and position control prototypes until we had one preferred design of each type (these control types are described in Section 2.1). We chose to use flexion-extension as the input angle because it allows for a much larger dexterous input range than radial and ulnar deviation [40, 43].

During our iterative design process, we conducted two qualitative pilot studies. In the first study, we gathered feedback from five participants in order to narrow down our approaches with a few high-level design decisions. Each participant tried each of eight different wrist-deflection scrolling prototypes for several minutes on a sample list (Fig. 1b). They then ranked them by preference and provided qualitative feedback. In the second study, we deployed the top two techniques and collected feedback from four participants to determine the best gain functions and constant values. We systematically switched the type of gain function or adjusted the value of a constant, and asked participants whether it had gotten better or worse. This continued until we found locally optimal values, which we averaged across the four participants for our user study. Herein we describe the designs of the final techniques as well as several key decisions that were made during the prototyping process. The specific constant parameters used in the prototypes are described in appendix A.

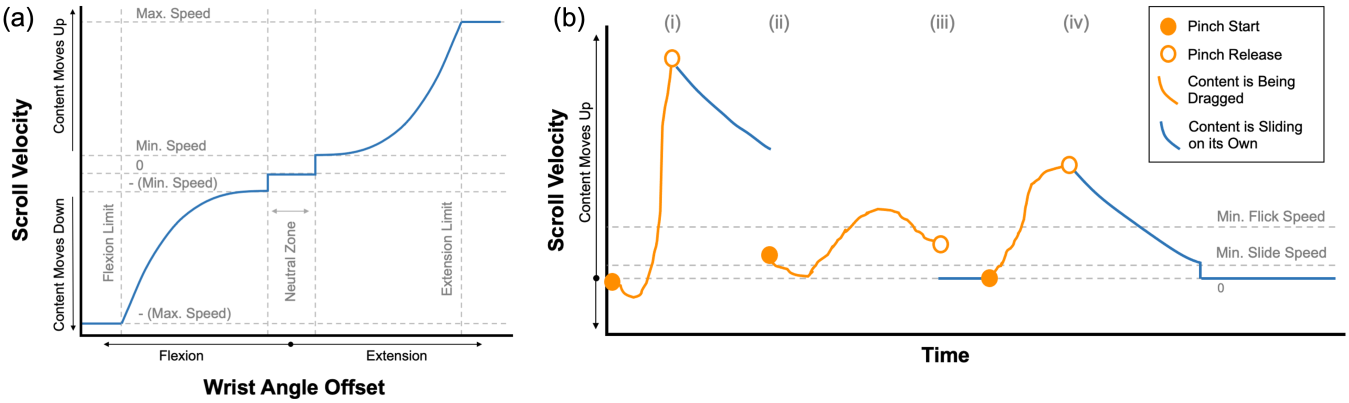


Figure 2: (a) Transfer function for the Wrist Joystick technique. (b) A diagram of example actions possible with the Wrist Drag technique. (i) The user flicks the scrollable content and it starts to slide. (ii) The user interrupts the slide by grabbing the content again. (iii) The user drops the content without flicking it. (iv) The user flicks the list again and it slows to a stop on its own.

3.1 Rate Control: Wrist Joystick

Wrist Joystick uses rate control and is inspired by scrolling with a physical joystick. It works in the following manner: Prior to using the technique the first time, the user completes a calibration routine that determines their comfortable range of wrist flexion and extension, and their neutral wrist angle position. Then when using the technique, the user makes a thumb-to-index finger pinch gesture to activate scrolling, and releases their pinch to deactivate it. While scrolling is activated, the content will scroll at a rate related to the angle of the user's wrist flexion/extension (Fig. 2a).

While most joysticks have an automatic re-centering mechanism, marking a clear neutral position, there is no such distinct boundary in wrist motion. Therefore, in Wrist Joystick, there is a small "neutral zone" around their calibrated neutral wrist angle in which the content does not move. Outside of this zone, the wrist angle is converted to a proportion from the edge of the neutral zone to the user's maximum comfortable point of flexion/extension. This proportion is cubed and the result is used to interpolate between a minimum scrolling speed and a maximum scrolling speed.

3.1.1 Fixed vs Relative Offset. Wrist Joystick measures the user's wrist angle with respect to a calibrated fixed neutral point, so each wrist deflection angle always maps to the same scrolling speed. Another option would have been to use a relative offset, where the neutral point would be reset whenever scrolling was activated. Participants in our first pilot study reported that with the relative offset they would often forget where they had started their pinch gesture, making it difficult to self-center and locate the slowest speeds. Participants would also frequently reach the limits of their wrist flexion/extension and find that they had not given themselves room to reach the scroll speeds they wanted, adding frustration when scrolling to a distant target. Therefore, we used the offset from a fixed point.

3.1.2 Transfer Function. The transfer function (Fig. 2a) is similar to the one used for pure rate control pointing by Tsandilas [49], who observed that "*transfer functions that grow rapidly around the zero position ... are sensitive to input precision*". We made similar observations, but found that adding a neutral angle zone with a speed of 0 and then interpolating from a higher minimum speed improved user control for precise scrolling. We theorize that this is because speeds very close to 0 are not useful, even for precise scrolling, so adding this discontinuity devotes a wider range of wrist angles to the moderately slow speeds that users are interested in.

3.2 Position Control: Wrist Drag

Wrist Drag is our position control technique and is analogous to touch-screen drag and flick interactions [1, 12, 39]. The user begins a pinch gesture to "grab" scrollable content and then changes the flexion/extension angle of their wrist to move the content a constant distance for every degree they have traveled. When the user releases their pinch, the content stays in its new position. If its speed at the time of release is higher than a certain threshold, the content will continue moving as if with momentum, gradually slowing to a stop with simulated friction (Fig. 2b). The friction is a simple combination of exponential decay and linear decay. In particular, the content's scrolling speed at frame n (s_n) is determined by the expression

$$s_n = s_{n-1} - \Delta t((xs_{n-1}) + y)$$

where x and y are constants and Δt is the time in seconds between two frames. When the sliding speed falls below a threshold, it automatically drops to zero. This is used to prevent lists that don't smoothly animate between items from advancing after they appear to be stopped.

4 USER STUDY

Wrist-deflection based scrolling techniques such as the ones we've developed above have not been explored as a method for interface control for XR, and yet they are promising because they enable freehand interaction and offer flexibility in arm position. Thus, to explore their potential, we conducted a user study towards the following goals: a) Explore potential performance trade-offs for our freehand, posture-independent techniques when compared to state-of-the-art controller and hand-tracking based techniques. b) Determine whether or not the wrist deflection techniques perform well in the arm-at-side posture. c) Assess the relative merits of rate control and position control for wrist deflection input. d) Analyze wrist scrolling behaviors and ergonomic behaviors to offer design insights for future development.

4.1 Apparatus

To detect users' angles of wrist flexion and extension agnostic of headset camera coverage, we used the same approach as RotoWrist [44] (i.e., eight time-of-flight (ToF) IR light modules distributed around a wristband as in Figure 3a). RotoWrist was found to achieve a cross-user median tracking error of 5.9° in flexion/extension. To detect pinch and release gestures, a pair of electrodes were strapped to the thumb and index finger respectively, similar to [25] (Fig. 3a). We conducted the study in virtual reality, using an Meta Quest 2 for the display [38].

4.2 Participants

Twenty-four right-handed participants were recruited to participate in the study (i.e., 12 male, 11 female, 1 non-binary, aged 24-54). Out of 5, they reported a median familiarity of 3 with virtual reality headsets, 4 with joystick controllers, and 1.5 with "mid-air gesture interactions."

4.3 Scrolling Techniques

We evaluated the two wrist techniques alongside state-of-the-art rate and position control XR scrolling techniques, which we refer to as Controller Joystick (Section 4.3.1) and Arm Drag (Section 4.3.2). These are analogous to Wrist Joystick and Wrist Drag respectively, so by analyzing the ways in which they differ we hoped to identify trade-offs and insights specific to wrist deflection scrolling.

4.3.1 Controller Joystick. The Meta Quest Touch Controller's thumbstick/joystick is used to drive scrolling. When the joystick is in its neutral position, the scrollable content does not move. When it is offset from that position, the content's position changes at a rate related to the vertical offset of the joystick. The same minimum speeds, maximum speeds, and interpolation function as the Wrist Joystick technique are used (Fig. 2a), with the width of the "neutral zone" always being 0 because the joystick's auto-centering makes it easy to return to exactly its neutral position.

4.3.2 Arm Drag. This technique is similar to the one used to scroll with hand tracking in the Meta Quest 2 [38]. A reticle position is defined where the Quest's default hand tracking driven raycast intersects with the plane of the scrollable interface. When the user begins pinching, they "grab" the scrollable content at the current reticle position. Then, any vertical movement of the reticle position "drags" the content with it until the user releases their pinch. From this point, it has identical flicking and sliding behavior to the Wrist Drag technique (Fig. 2b), with the same simulated friction parameters.

Pinches were detected using the same apparatus as the wrist techniques, which was more robust to different hand poses than the vision-based pinch detection. Also, we did not show the user's hand, ray, or reticle in VR to avoid distraction and because the other techniques had no visual component. Users were able to grab and scroll even if their reticle position was outside the bounds of the scrollable interface so they did not need to worry about pointing in exactly the right place. For all tasks, clicking signalled the completion of the goal regardless of the reticle position.

4.3.3 Postures. All four techniques were evaluated in an arm-in-front posture, with participants seated and their arm resting on an armrest (Fig. 1c, left). We selected this posture because we were concerned that arm fatigue from prolonged arm extension may impact scrolling behavior over the course of the study duration [11, 20]. We had several variables to balance, so we wanted to minimize the effect of fatigue and enable valid comparisons of scrolling behaviors under close-to-ideal circumstances. Participants were instructed to keep their elbows on the armrest throughout all arm-in-front trials. When using the wrist deflection techniques, participants were also advised to keep their palms facing down, to encourage proper flexion and extension movement, but this was not enforced beyond regular reminders.

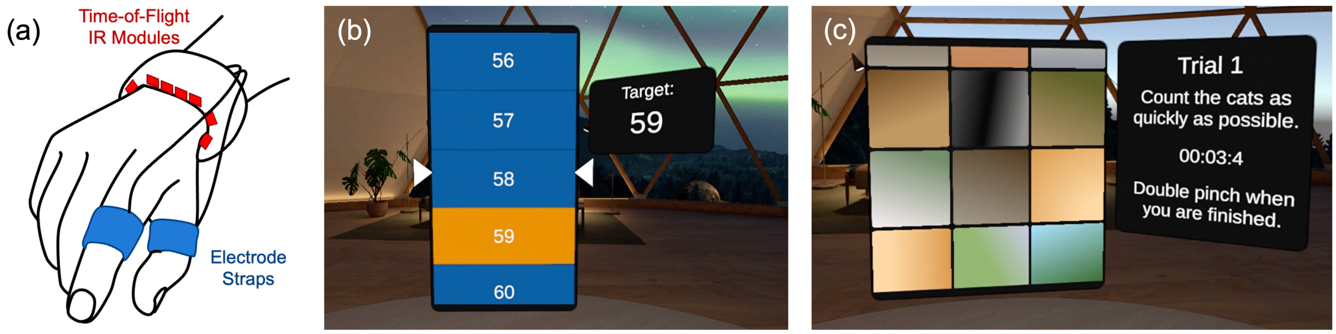
Because arm-posture independence is one motivation for wrist deflection interactions, we included a final condition evaluating the wrist techniques in a standing arm-at-side posture (Fig. 1c, right). Arm-at-side posture creates an indirect mapping between wrist movement and scrolling movement, and so it is possible that scrolling performance might suffer when the technique is carried out with one's arm by their side.

4.4 Scrolling Tasks

Different scrolling methods may perform differently depending on the nature of the scrolling task. To capture a broader picture of our techniques' performance, we considered two task types (Fig. 3b and 3c). The first task, Reciprocal Selection, emphasized the fast acquisition of a target in a known location. The second task, Counting, resembled a more casual browsing task in which the user needs to pay attention to the content as they scroll through it.

Both tasks involved a list interface that was vertically scrollable and moved smoothly without any snapping. The lists were positioned 2 meters in front of the participant at whatever height the participant deemed most comfortable. Both tasks included a "click" gesture to indicate completion. For all freehand techniques this gesture was a double-pinch (that is, two quick pinch and release motions within a short time) and for the Controller Joystick this gesture was pulling the controller's trigger button. To avoid accidental scrolling when the user pinches to select (i.e., the "Heisenberg Effect" [3]), a 0.15 second delay was added to all freehand techniques between the start of pinching and the list's movement. The drag techniques would override this delay if the user moved the list more than 20cm in that time, such as when performing a flick. These values were determined in our second pilot study.

4.4.1 Reciprocal Selection Task. This task was a variant of the Fitts' reciprocal tapping task that has been used in prior research [21, 50]. Participants were shown a vertically scrollable list of boxes numbered from 1 to 200, with two white arrows fixed in the center pointing inward, and a virtual viewport that was 140 centimeters tall (Fig. 3b). The boxes all had the same height and were blue



Trial 1
Count the cats as quickly as possible.
00:03:4
Double pinch when you are finished.

Figure 3: (a) The user study apparatus consisted of a wristband with eight time-of-flight IR light modules pointed towards the hand, and two electrode finger straps for the thumb and forefinger. (b) The Reciprocal Selection task involved scrolling back and forth between two targets as quickly as possible. Here it is shown with a 30 centimeter target size. (c) The Counting task involved counting the number of cats that appeared in a list of photos of animals (photos omitted here).

except for one target which was orange. The target number was also displayed in a box next to the list. To vary the level of precision required, small (15 centimeters) and large (30 centimeters) target heights were used.

Participants were instructed to scroll until the target box was between the central arrows, then perform a click to select the target. When they selected the target, it turned blue and they were given a new target. The users could not proceed to the next trial until they had selected correctly. Within a given trial, the targets would alternate between 50 and a larger number for 10 total selections (i.e. “*phases*”). Each phase consisted of a single scrolling and clicking task which started with a prompt and ended with a double pinch. Participants were told to alternate between selecting these two targets as quickly and accurately as possible. Small (30 centimeter), medium (270 centimeter), and long (960 centimeter) distances were used. Each block of the Reciprocal Selection task consisted of one 10-phase trial for each possible *Target Size* and *Scroll Distance* pair.

4.4.2 Counting Task. This task was inspired by prior research [12] and was designed to simulate the smooth scrolling and cognitive load of real-world browsing tasks. Participants were shown a grid of 33 rows of 3 photos (Fig. 3c). The set of photos were manually selected from The Oxford-IIIT Pet Dataset [37]. Most of these photos were of dogs, but some (anywhere from 6 to 14, chosen randomly) were of cats. Each list contained a randomly selected subset of dogs and a randomly selected subset of cats (with the appropriate number of each), shuffled into a random order. Participants were asked to scroll to the bottom of the list and count the number of cats as quickly and accurately as possible. They performed a click gesture to reveal the list and begin the timing, and clicked again to hide the list and stop the timer. After the list was hidden, they reported the number of cats they counted. Each block of the Counting task consisted of one such trial.

4.5 Design and Procedure

A repeated-measures design with within-subjects factors was used. The independent variables were *Technique* (Arm Drag, Wrist Drag, Wrist Joystick, Controller Joystick) and *Task* (Reciprocal Selection and Counting). Within the Reciprocal Selection task, we also varied *Target Size* (15 and 30 centimeters) and *Scroll Distance* (30, 270, and 960 centimeters). For the wrist techniques, we included a second posture condition for a total of two *Postures* (arm-in-front and arm-at-side).

The study consisted of four back-to-back sessions with brief (i.e., less than five minute) breaks in between, lasting approximately two hours total. Each session was dedicated to a single scrolling technique. At the start of a session, participants could practice with the technique for as long as they wanted, and they completed one practice trial before their first block of each task. After all arm-in-front blocks in a session, participants completed a qualitative survey about the technique. For the wrist techniques they completed a second survey after the arm-at-side blocks. After all four sessions, participants completed a final survey comparing the *Techniques*, *Tasks*, and *Postures*.

Across participants we counterbalanced the presentation of *Technique* as well as the order of the 6 *Size* x *Distance* pairs in each block of the Reciprocal Scrolling task. We did not counterbalance *Task* order; instead we always presented 2 blocks of the Reciprocal Scrolling task followed by 3 blocks of the Counting task. We also did not counterbalance *Posture* for the wrist techniques; participants first completed all arm-in-front trials and a survey about them, then they transitioned to the arm-at-side posture and completed 1 additional block of the Reciprocal Scrolling task, 3 blocks of the Counting task, and an additional survey. This was done so that all four techniques could be compared in the arm-in-front posture without any learning effects from arm-at-side trials, since some techniques did not have this condition. Each *Task* x *Posture* combination was considered independently, as our goal was not to directly compare these with each other but instead to see how our techniques performed in multiple contexts.

Thus the final experiment design was:

- **Arm-in-Front, Reciprocal Selection**: 4 Techniques x 2 Blocks x 3 Distances x 2 Sizes x 10 Phases
- **Arm-in-Front, Counting**: 4 Techniques x 3 Blocks
- **Arm-at-Side, Reciprocal Selection**: 2 Techniques x 1 Block x 3 Distances x 2 Sizes x 10 Phases
- **Arm-at-Side, Counting**: 2 Techniques x 3 Blocks

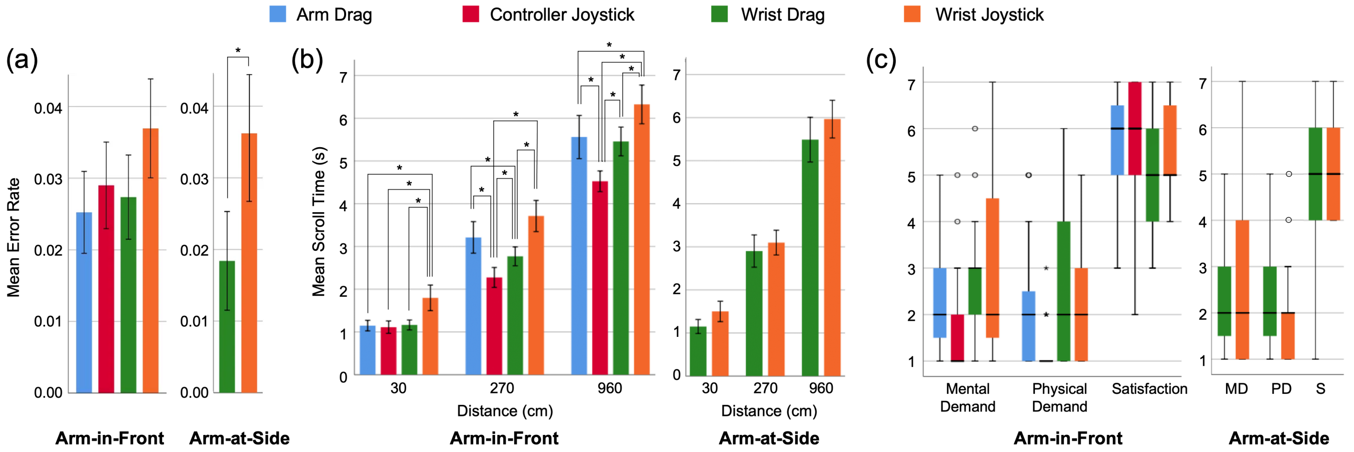


Figure 4: Results for the Reciprocal Selection task. Error bars represent 95% CI, * denotes a significant difference. (a) Mean error rate for each technique and posture. (b) Mean scroll times by technique, posture, and target distance. (c) Subjective scores for the Reciprocal Selection task.

4.6 Measures

The primary metric for the Reciprocal Selection task was scroll time, which was measured as the duration starting from the first movement in a phase until the start of the correct click gesture. The primary metric for the Counting task was scroll time, which was measured starting from the moment the list of photos was revealed until the start of the click gesture indicating completion. We also report on the percentage of errors, subjective scores, and other metrics such as total wrist movement to help us understand user behaviors.

5 RESULTS

We first discuss task performance and subjective scores for the Reciprocal Selection task followed by the Counting task. We then present participants' overall preference rankings. For readability, all statistics and some results are provided in appendix A. Tables 2, 3, and 4 contain the results of our analyses on error rates, task completion time, and subjective scores, respectively.

5.1 Reciprocal Selection Task

Overall, Wrist Drag performed better than Wrist Joystick at this task, having consistently faster scroll times and occasionally lower error rates. Wrist Drag's arm-in-front performance was also comparable with Arm Drag's. However Controller Joystick, which enables precise finger-level movements, generally outperformed all other techniques and was reported to be the least physically and mentally demanding. Looking at the mean scroll times in the arm-at-side posture, both wrist techniques retain their scroll time performance from the arm-in-front posture.

Note that arm-at-side trials may have benefited from learning effects, since they always took place after arm-in-front trials. For this reason we avoid direct analysis across postures and observe only that performance was retained: it did not noticeably suffer when users transitioned to an indirect arm-at-side posture, which is promising evidence that wrist deflection techniques can support posture-independent interaction.

5.1.1 *Errors & Outliers.*

In the arm-in-front posture, the rate of erroneous phases where an incorrect target was selected was 1.5% of all phases (Fig. 4a). There were no significant differences between different techniques. In the arm-at-side posture, this rate was 2.7%, and the error rate for Wrist Drag was significantly lower than Wrist Joystick, although both rates were fairly low. For the scroll time analysis, we removed these erroneous phases. We further removed outliers outside three standard deviations which constituted 2.7% of all phases in the arm-in-front posture and 1.3% in the arm-at-side posture.

5.1.2 *Scroll Time.*

For the arm-in-front posture, a 4-way RM-ANOVA was conducted to analyze the mean task completion time for the *Technique, Block, Distance*, and *Size* variables (Fig. 4b and 9). Main effects were found for all four variables. The effects of *Distance*, *Size*, and *Block* were along expected lines given Fitts' Law and learning effects, and are not discussed since our focus is on the effects relating to *Technique*. 2-way interactions were found between $Technique \times Distance$ and $Technique \times Size$. No 3-way or 4-way effects were found, nor were any other 2-way effects found.

We further analyzed simple main effects of *Technique* for each *Distance* and *Size* level and conducted pairwise comparisons with Bonferroni corrections where significant simple main effects were found. The results revealed that Controller Joystick had significantly lower scroll times than the other three techniques for the 270 and 960 distances. Arm Drag and Wrist Drag mostly had similar performance to each other, with Arm Drag having a higher scroll time for only the 270 distance. Wrist Joystick had significantly higher scroll times than the other three techniques for the 30 and 960 distances and higher scroll time than Wrist Drag and Controller Joystick for the 270 distance. For both target sizes, the main effects of *Technique* were similar to those for the 960 distance: Wrist Joystick had significantly higher scroll times than the other

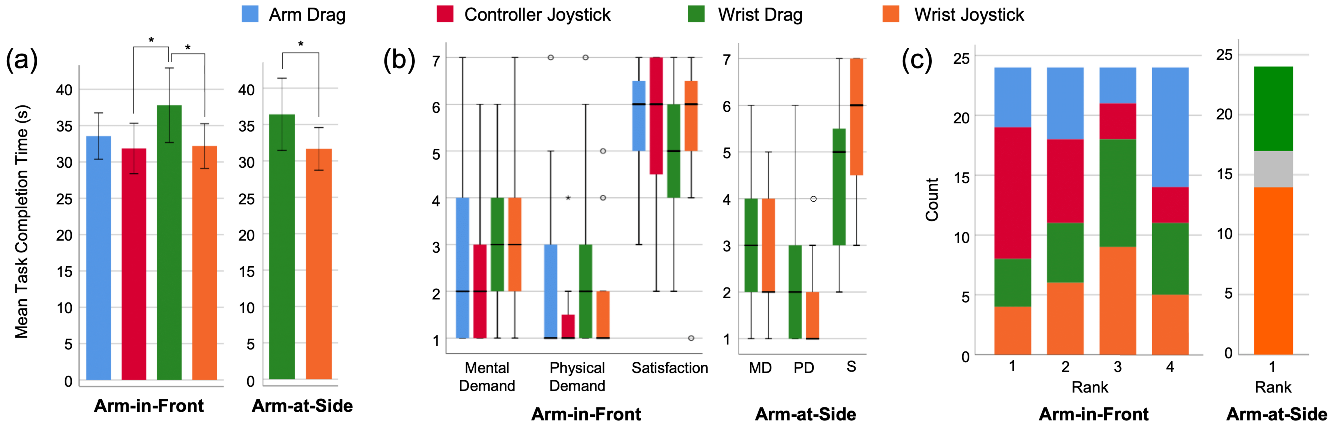


Figure 5: (a) Mean scroll times for the Counting task in terms of technique and posture (error bars represent 95% CI, * denotes a significant difference). (b) Subjective scores for the Counting task. (c) Subjective rankings of the four scrolling techniques for the arm-in-front posture and the two wrist scrolling techniques for the arm-at-side posture. Some participants expressed no preference in the arm-at-side posture; we represent them with gray.

three techniques and Controller Joystick had significantly lower scroll times than the other techniques.

Our results for the arm-at-side posture were very similar to arm-in-front. We conducted a 3-way RM-ANOVA for mean scroll time for the *Technique, Distance*, and *Size* variables (Fig. 4b and 9a) (there was only 1 block for arm-at-side), and found main effects for all three variables, with the effects of *Size* and *Distance* being along expected lines. No 2-way or 3-way effects were found, but pairwise comparisons with Bonferroni adjustments showed that the Wrist Drag technique once again had a significantly lower scroll time than the Wrist Joystick technique.

5.1.3 Subjective Scores.

For the arm-in-front posture, a non-parametric Friedman ANOVA test found a significant effect of *Technique* on the *Physical Demand* and *Mental Demand* (Fig. 4c). Pairwise Wilcoxon tests showed that Controller Joystick had significantly lower physical and mental demand than the other three techniques. No other significant effects were found. For the arm-at-side posture, Wilcoxon signed-rank tests found no significant effects of *Technique* on any subjective measure.

5.2 Counting Task

This task showed a reversal from the previous one: Wrist Joystick was faster than Wrist Drag in both postures. It also had lower physical demand and higher satisfaction in the arm-at-side posture. This could be because with Wrist Joystick, the user could simply keep their wrist still to scroll smoothly, while Wrist Drag required constant movement that could have cost energy or focus. Wrist Joystick also had comparable performance with both state-of-the-art techniques. Once again, both wrist techniques retained their arm-in-front performance in the arm-at-side posture.

5.2.1 Task Completion Time.

A 1-way RM-ANOVA found a significant effect of *Technique* on task completion time for the arm-in-front posture (Fig. 5a). Pairwise comparisons with Bonferroni adjustments showed that Wrist Drag took significantly longer than Wrist Joystick and Controller Joystick. For the arm-at-side posture, Wrist Drag again had significantly longer scroll times than Wrist Joystick.

5.2.2 Subjective Scores.

Non-parametric Friedman tests showed significant effects of *Technique* on *Physical Demand* and *Satisfaction* for the arm-in-front posture (Fig. 5b). Pairwise Wilcoxon tests showed that participants reported that the Wrist Drag technique had significantly higher physical demand and significantly lower satisfaction than Controller Joystick. For arm-at-side, Wrist Drag had significantly higher physical demand and lower satisfaction than Wrist Joystick. No other significant effects were found.

5.3 Ranking Preferences

In the final survey, participants were asked to rank all four scrolling techniques in order of their preference (Fig. 5c). Participants had no strong agreement about which techniques they most preferred. The Controller Joystick technique looks somewhat more preferred (e.g., *"Controller joystick was familiar therefore easy to do"*, P4), and Arm Drag seems to be least preferred. When asked which wrist technique they preferred for arm-at-side scrolling, 14 participants said Wrist Joystick, 7 said Wrist Drag, and 3 said they were similar. Both wrist techniques were thought to be more fun, intuitive, and easy than the other by different participants (e.g., *"I really enjoyed the wrist drag because it was less work to put in, yet it had a familiar feeling to swiping on a device"*, P1 and *"I loved how easily you can rev up and slow down with wrist joystick. It made it feel like I was completely in control."*, P20).

6 ANALYZING AND IMPROVING WRIST TECHNIQUES

The performance results show that both wrist scrolling techniques can perform comparably with an analogous state-of-the-art technique for a particular task, and they can retain that performance even in the arm-at-side posture. These are encouraging results with respect to the viability of freehand, posture-independent scrolling

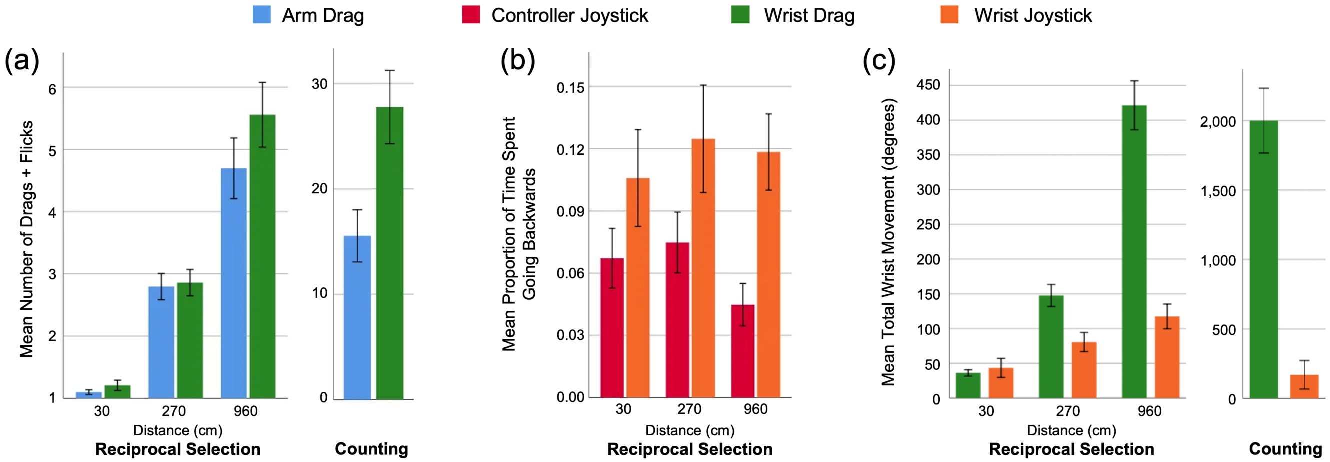


Figure 6: Various behavior metrics from the user study (error bars represent 95% CI). (a) Number of total drag and flick gestures for Arm Drag and Wrist Drag. (b) Proportion of time spent going backwards (that is, opposite the direction from the starting point to the target) in the Reciprocal Selection task for Controller Joystick and Wrist Joystick. (c) Total amount of wrist movement for Wrist Drag and Wrist Joystick in both tasks.

using wrist deflection. However, the results also show that Wrist Drag does not perform as well in the Counting task and Wrist Joystick does not perform as well on the Reciprocal Selection task. Therefore, in this section, we analyze scrolling behaviors from the following three perspectives to gain insights on how to improve wrist deflection scrolling: a) Wrist Joystick vs Controller Joystick behavior, b) Wrist Drag vs Arm Drag behavior, c) Wrist Drag and Wrist Joystick ergonomics.

6.1 Wrist Joystick Compared with Controller Joystick

There was a significant gap in performance between Wrist Joystick and Controller Joystick for the Reciprocal Selection task. This was despite both techniques using the same gain function with the same range of speeds. One reason for this could be the Controller Joystick's high input precision and accuracy, but rate control techniques are not necessarily very sensitive to input precision [49]. Another reason could be that participants had less intuitive control of Wrist Joystick (e.g., *"I would definitely just prefer the controller joystick over the wrist joystick as it is less work and easier to control."*, P21). We analyzed the time spent traveling in the wrong direction for both techniques and found that participants spent a significantly larger chunk of each trial traveling in the wrong direction with Wrist Joystick. This could be due to mistakes during the initial wrist deflection or correcting overshooting mistakes (Fig. 6b).

To learn more about the difference in user behavior with these techniques, we compared the amount of time spent with the joystick and the wrist at each angle of deflection (Fig. 7). With the controller, participants primarily made use of the most extreme angles and angles very close to zero, with almost no time spent in between. In contrast, Wrist Joystick shows a much more even spread of input values with different peaks depending on the target distance. With this technique, participants seem to have spent more time gradually accelerating and decelerating.

Part of this could be due to the extremely minimal movement required to fully deflect the Controller Joystick. But another potential reason is the lack of feedback from the Wrist Joystick about the current angle of deflection. Physical joysticks have an elastic force pulling them back towards the center, and this has been shown to improve the performance of rate control interactions [8, 56]. Without this, participants may have been less confident quickly changing their wrist angle, instead relying on their observation of the list's movement.

One potential solution to improve Wrist Joystick is to generate haptic feedback within the wristband based on the user's amount of deflection to increase their intuition of the input space. Another solution would be to reduce the need for precise continuous control in the first place. This could be done by adding support for a discrete gesture to "nudge" the scrollable content by a fixed distance (like the height of one list item). Users could then use this gesture when making short movements or final corrections without ever needing to quickly access slow scroll speeds.

6.2 Wrist Drag Compared with Arm Drag

Wrist Drag had similar task completion times to Arm Drag, despite it having a much more limited input space, which suggests that the additional degrees of freedom supported by mid-air hand tracking do not necessarily improve performance for this type of one-dimensional scrolling. The two position control techniques also showed similar movement patterns in the Reciprocal Selection task, including similar numbers of drag/flick actions (Fig. 6a). However, in the Counting task, where it was not very practical to flick the list, participants used significantly more drag/flick actions with Wrist Drag than with Arm Drag. It appears that, when scrolling slowly, participants make use of more of their input range to reduce the need for clutching. In such cases where extended slow browsing is required, it could then be useful to increase Wrist Drag's input range however possible, such as with a curved wrist deflection path

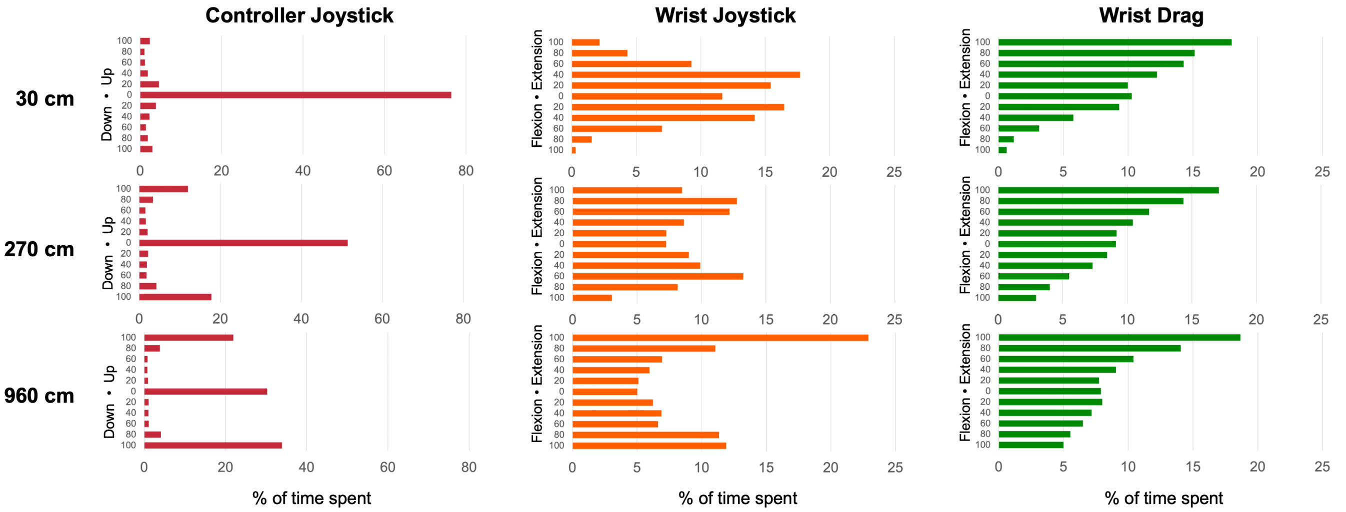


Figure 7: Mean percentages of time spent with the wrist or joystick at different deflection angles for three scrolling techniques in the Reciprocal Selection task. In order to better show patterns, angles are expressed as a percentage of the user's total range in that direction (for the wrist techniques this was calibrated whenever a new wrist condition was started and posture was changed). Note that the Controller Joystick graphs have a significantly larger x-axis scale than those of the wrist techniques.

(see Section 6.3.2) or even a complete circle that removes the need for clutching, similar to an iPod's scroll wheel [33, 50].

6.3 Wrist Ergonomics

Wrist deflection is a valuable form of input because it can be free-hand and posture-independent. We investigate multiple ergonomic metrics here with the goal of optimizing our wrist techniques as well as other wrist deflection-based interactions.

6.3.1 Amount of Wrist Movement. We measured the total wrist movement (i.e., cumulative degrees rotated) for both wrist techniques across both tasks (Fig. 6c). This revealed that participants moved their wrist significantly more with Wrist Drag than with Wrist Joystick in both tasks, with the difference increasing over longer scroll durations. In the Counting task, where flick gestures were not suitable, participants moved an average of over 7 times more with Wrist Drag. As P11 said, *"for long scrolling it was less intense on my wrist to do the wrist joystick"*. The need for constant movement in some situations is an inherent drawback of position control, and constant flexion/extension movement can be particularly uncomfortable [7, 24]. One potential improvement, then, could be to use a hybrid of position and rate control such as the ones proposed for pointing by Casiez et al. [9] and Tsandilas et al. [49], where the content can scroll autonomously under certain circumstances.

6.3.2 Time Spent Deflected. We measured the total percentage of time participants spent with their wrist at every angle of deflection for both wrist techniques. Figure 7 shows these distributions for the Reciprocal Selection task and reveals very different patterns for the two techniques. Because Wrist Drag was based on relative movement, participants had some freedom as to their absolute wrist angle. For all distances they generally seemed to prefer keeping their wrist extended (such as after a flick upwards) over keeping it flexed. With Wrist Joystick, they did not have as much freedom and spent a large portion of time at certain deflection angles while the list scrolled to their target. This may have been uncomfortable, especially while holding a thumb-to-finger pinch [7, 24]. P18 said *"my wrist slightly fatigued in the fully flexed and extended positions on the longer scrolls with the pinching"*. One way to mitigate this issue could be to provide a way for the user to scroll without sustained pinching (such as using a single pinch and release to toggle the scroll mode instead).

6.3.3 Wrist Movement Path. We created density plots for each participant to show the wrist deflection positions that they occupied during any trial with a wrist technique, including their radial and ulnar deviation (a subset is in Figure 8, however all 24 are in Figure 10 in the appendix). We observed that several participants moved their wrist along a path that was fairly consistent but not exemplary of perfect flexion/extension (as they were instructed to do). Their movement was often tilted diagonally (as with P1) or followed a curved path (as with P15). Several participants commented that they would have rather angled their arm (*"it would be a little better if you accounted for the fact that some people's wrists naturally face diagonally outward rather than straight out when standing naturally and its a bit hard to keep your wrists straight facing."*, P20). This suggests that there is an opportunity for personalization, where if an algorithm could explicitly or implicitly adapt to a participant's preferred path of motion, a larger range of input values could be captured in their comfort zone. As there are similar movement shapes across sessions and postures for the same participant (though sometimes translated after recalibration, as with P23), there is thus the potential for reusable, personalized models.

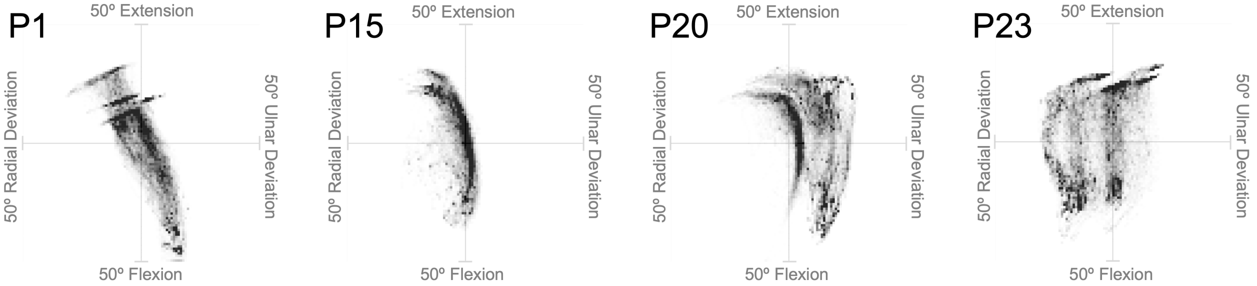


Figure 8: Density plots of the wrist angles of four participants (all tasks and postures, both wrist techniques). The graph's axes are analogous to the motion of the right wrist when viewed from a first-person perspective. The ideal behavior is a perfect vertical line indicating that the user's hand only moves along flexion-extension without any deviation, but many participants demonstrated tilted or curved shapes instead.

7 DISCUSSION

Our study is the first in-depth evaluation of scrolling techniques based on wrist deflection angles. This kind of input is distinctive because it is freehand but defined relative to the user's arm rather than the world (as with device tilting) or an interface (as with ray casting). This approach gives the user the flexibility to control any interface in any arm posture, which would reduce friction in many extended reality scenarios. Our results demonstrate that wrist deflection is an effective input modality for XR scrolling in both arm-in-front and arm-at-side postures.

Though our wrist techniques did not match the physical Controller Joystick in terms of participant preference or reciprocal selection speed, they may be a desirable alternative to vision-based ray casting in situations requiring freehand interaction. In both of our study's tasks, one wrist technique performed comparably to Arm Drag in an arm-in-front posture, and both techniques retained their task performance in an arm-at-side posture which Arm Drag cannot support. This added flexibility could enable users to perform quick selections or extended browsing without the social or ergonomic costs associated with holding their arm out in front of them [11, 20, 42], or the friction of changing their arm posture at all.

Besides verifying the feasibility of wrist deflection scrolling, our study compared two wrist scrolling techniques (i.e., Wrist Joystick and Wrist Drag, that use rate control and position control respectively) for two kinds of scrolling tasks. In the Reciprocal Selection task, which involved rapid and precise scrolling, Wrist Drag had significantly better performance than Wrist Joystick. But in the Counting task, that involved slow sustained scrolling, Wrist Joystick not only outperformed Wrist Drag but also required significantly less wrist movement.

Our findings are generally consistent with previous research comparing these control orders in other contexts [6, 14, 27, 35, 48], but we gain additional insight about wrist deflection input in particular through examining behavioral metrics and comparing with analogous state-of-the-art techniques. Both wrist techniques were very similar to their state-of-the-art counterpart in the task for which they were strongest. But the ways in which they differed from their analog in their weakest task indicate potential paths to improve performance. For example, participants using the Wrist Joystick seemed to be more cautious changing their wrist angle than they were with the Controller Joystick, and had significantly slower scroll times in the Reciprocal Selection task. Wrist Joystick may improve with additional feedback (such as haptics) to the user about their current wrist deflection state. Finally, by analyzing wrist movement over time, we identified several ways in which the ergonomics of wrist deflection impact users' preferred movements. These findings can inform future development of wrist deflection interactions.

7.1 Application for Extended Reality

We envision wrist deflection scrolling as a practical interaction technique for virtual, augmented, and mixed reality devices. Though our study was conducted in a purely virtual environment, we expect our findings would mostly extend to AR and MR scenarios as well. The differences that would arise, such as increased environmental distractions and users' ability to see their own hands, present interesting research questions but do not negate our evidence that users can learn and apply wrist movement alone for effective interaction in new computing environments.

A practical XR system would also need to support more interactions than just scrolling and selection. Because both of our proposed techniques require a sustained pinch gesture to activate scrolling, they could easily be implemented alongside interactions that are based only on movement and quick pinches, such as previously proposed methods of pointing, text entry, and discrete gestures using wrist deflection [15, 16, 44], though these haven't been evaluated in XR. Our techniques could also complement a vision-based hand tracking system, such as by using hand tracking for complex tasks like 3D object manipulation, and using wrist deflection scrolling when it would be more convenient (e.g., a quick selection from a list while waiting in line) or comfortable and discreet (e.g., browsing a news feed on the bus).

7.2 Limitations and Future Work

Our study explored a range of scrolling task parameters and techniques, but there remains room for more detailed investigation and optimization of wrist deflection scrolling in future work. Some potential improvements to each technique are proposed in Section

6. Further research could also quantitatively optimize transfer functions through approaches like those in [1, 29, 39], or augment these techniques with other technology like gaze tracking [28], which is feasible in an XR headset. Comparisons with more scrolling techniques (e.g., mobile devices) and evaluations for more use cases (e.g., scrolling in two dimensions, scrolling with lists that snap into place, scrolling while walking, or scrolling in conjunction with other interactions) could provide additional insights.

One important factor that we did not measure in this work is each technique's impact on fatigue and discomfort over time. We predict that use of the wrist scrolling techniques in an arm-at-side posture would result in lower fatigue than extended use of midair interactions [11, 20], and in Section 6 we identified potential sources of discomfort for each wrist technique. It would be valuable to verify and expand on these ideas through a user study with longer sessions and no arm rest.

This work also did not investigate the impact of sensing accuracy. There have been several proposed methods for measuring a person's wrist deflection [15, 16, 44, 46, 52, 55], and our wrist scrolling techniques could be implemented with any of them. It's possible that more accurate wrist angle input could improve performance with our techniques or enable the same performance with less wrist movement. It would be useful to evaluate our techniques' performance with different kinds of sensing hardware and with different levels of accuracy, to get a clearer idea of how affordable, comfortable, and usable a realistic product could be.

8 CONCLUSION

In this paper, we presented two scrolling techniques for extended reality that are driven by wrist deflection gestures. Wrist deflection input is not only practical to sense with a wristband, but can be simultaneously freehand and arm posture-independent, creating lower friction than existing XR input methods. In a user study with 24 participants, we confirmed the viability of both techniques in multiple arm postures and showed their relative strengths and weaknesses. By comparing ergonomic and behavioral metrics with state-of-the-art analogs, we provided design insights specific to wrist-deflection input. This work lays the foundation for further research into this promising form of XR interaction.

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A APPENDIX

Constant	Reciprocal Selection Task	Counting Task
Joystick Max Speed (cm/s)	350	160
Joystick Min Speed (cm/s)	30	30
Wrist Drag Rate (cm/degree)	1.75	1.5
Exponential Friction Constant x	0.8	0.9
Linear Friction Constant y	120	120
Minimum Flick Speed (cm/s)	90	90
Minimum Slide Speed (cm/s)	10	2
Freehand Scrolling Activation Delay (s)	0.15	0.15

Table 1: The constant parameters used in the study. In some cases they differ between tasks, the way different interfaces often set their own scroll rates. Values for both tasks were determined in our second qualitative pilot study.

		ANOVA on Technique
RECIPROCAL SELECTION	FRONT	$F(2.332, 53.627) = 1.169$ $p > 0.05, \eta^2 = 0.048$
	SIDE	$\mathbf{F(1, 23) = 6.432}$ $\mathbf{p < 0.05, \eta^2 = 0.219}$

Table 2: The results of our analysis on error rate in the Reciprocal Selection task.

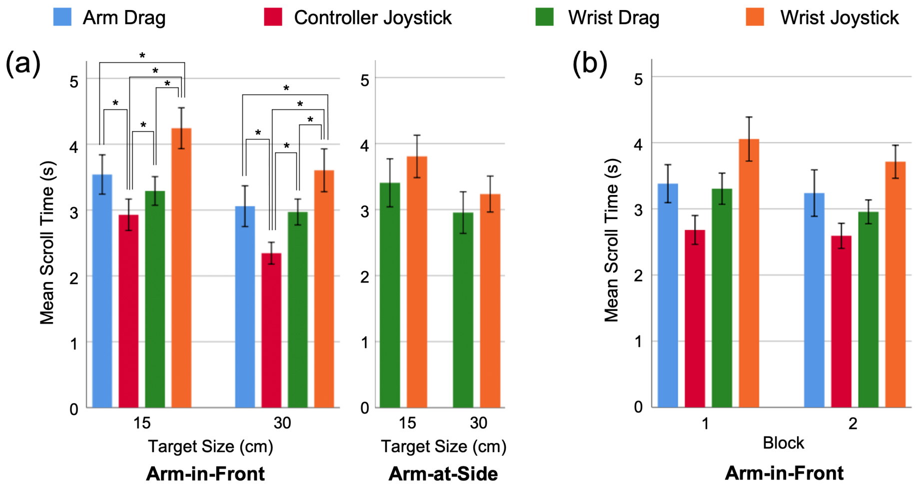

Figure 9: Additional results for the Reciprocal Selection task. Error bars represent 95% CI, * denotes a significant difference. (a) Mean scroll times by technique, posture, and target size. (b) Mean scroll times by technique and block.

		Effect	**ANOVA on Scroll Time**	**1-way ANOVA for Simple Main Effects**	**Pairwise Results**
Reciprocal Selection Task	Arm-in-Front	Technique	**$F(3, 60) = 32.039$ $p < 0.001, \eta^2 = 0.616$**	NA due to interaction effects	
		Block	**$F(1, 20) = 41.478$ $p < 0.001, \eta^2 = 0.675$**	[Skip]	
		Distance	**$F(1.265, 25.299) = 1012.655$ $p < 0.001, \eta^2 = 0.981$**	NA due to interaction effects	
		Size	**$F(1.000, 20.000) = 182.530$ $p < 0.001, \eta^2 = 0.901$**	NA due to interaction effects	
		Technique × Block	$F(1.981, 39.621) = 1.694$ $p > 0.05, \eta^2 = 0.078$		
		Technique × Distance	**$F(3.899, 77.987) = 10.819$ $p < 0.001, \eta^2 = 0.351$**	**D = 30: $F(1.681, 38.660) = 17.507$ $p < 0.001, \eta^2 = 0.432$**	WJ > AD, CJ, WD ($p < 0.05$ for these)
				D = 270: $F(3, 69) = 30.464$ $p < 0.001, \eta^2 = 0.570$	CJ < AD, WD, WJ; WD < AD, WJ ($p < 0.05$ for these)
				D = 960: $F(3, 69) = 27.373$ $p < 0.001, \eta^2 = 0.534$	WJ > AD, CJ, WD; CJ < AD, WD ($p < 0.05$ for these)
		Technique × Size	**$F(2.373, 47.453) = 7.332$ $p < 0.005, \eta^2 = 0.268$**	**S = 15: $F(3, 69) = 39.873$ $p < 0.001, \eta^2 = 0.634$**	WJ > AD, CJ, WD; CJ < AD, WD ($p < 0.05$ for these)
				S = 30: $F(3, 69) = 29.513$ $p < 0.001, \eta^2 = 0.562$	WJ > AD, CJ, WD; CJ < AD, WD ($p < 0.05$ for these)
	Arm-at-Side	Technique	**$F(1, 23) = 7.653$ $p < 0.05, \eta^2 = 0.250$**	NA	WD < WJ
		Distance	**$F(1.384, 31.829) = 611.993$ $p < 0.001, \eta^2 = 0.964$**	[Skip]	[Skip]
		Size	**$F(1, 23) = 37.886$ $p < 0.001, \eta^2 = 0.622$**	NA	[Skip]
		Technique × Distance	$F(1.693, 38.936) = 1.084$ $p > 0.05, \eta^2 = 0.045$		
		Technique × Size	$F(1, 23) = 1.223$ $p > 0.05, \eta^2 = 0.050$		
Counting Task	Front	Technique	**$F(2.069, 47.592) = 5.734$ $p < 0.005, \eta^2 = 0.200$**	NA	WD > CJ, WJ ($p < 0.05$ for these)
	Side	Technique	**$F(1, 23) = 8.227$ $p < 0.01, \eta^2 = 0.263$**	NA	WD > WJ ($p < 0.05$ for these)

Table 3: The results of our ANOVA analysis on task completion time. D = Distance, S = Target Size, CJ = Controller Joystick, WJ = Wrist Joystick, AD = Arm Drag, WD = Wrist Drag. Significant stats are bolded. For a significant 2-way interaction effect, multiple 1-way ANOVA tests were conducted for simple main effects. Greenhouse Geisser correction was applied wherever sphericity was violated. Posthoc pairwise comparisons included Bonferroni adjustments. [Skip] denotes that we do not include posthoc analyses for Block, Distance or Size main effects, since those effects were along expected lines and our focus was on effects relating to Technique.

		Mental Demand (MD)	**MD Pairwise**	**Physical Demand (PD)**	**PD Pairwise**	**Satisfaction (S)**	**S Pairwise**
Reciprocal Selection	Front	**$\chi^2(23, 3) = 14.965$ $p < 0.005$**	CJ < AD, WD, WJ	**$\chi^2(23, 3) = 15.039$ $p < 0.005$**	CJ < AD, WD, WJ	$\chi^2(23, 3) = 7.645$ $p > 0.05$	
	Side	$\chi^2(23, 1) = 0.077$ $p > 0.05$		$\chi^2(23, 1) = 2.250$ $p > 0.05$		$\chi^2(23, 1) = 0.000$ $p > 0.05$	
Counting	Front	$\chi^2(23, 3) = 6.676$ $p > 0.05$		**$\chi^2(23, 3) = 13.135$ $p < 0.005$**	WD > CJ	**$\chi^2(23, 3) = 17.262$ $p < 0.005$**	WD < CJ
	Side	$\chi^2(23, 1) = 1.143$ $p > 0.05$		$\chi^2(23, 1) = 4.765$ $p < 0.05$	WJ < WD	$\chi^2(23, 1) = 9.000$ $p < 0.005$	WJ > WD

Table 4: The results of our Friedman test analysis on subjective scores. Pairwise comparisons were done using Wilcoxon tests.

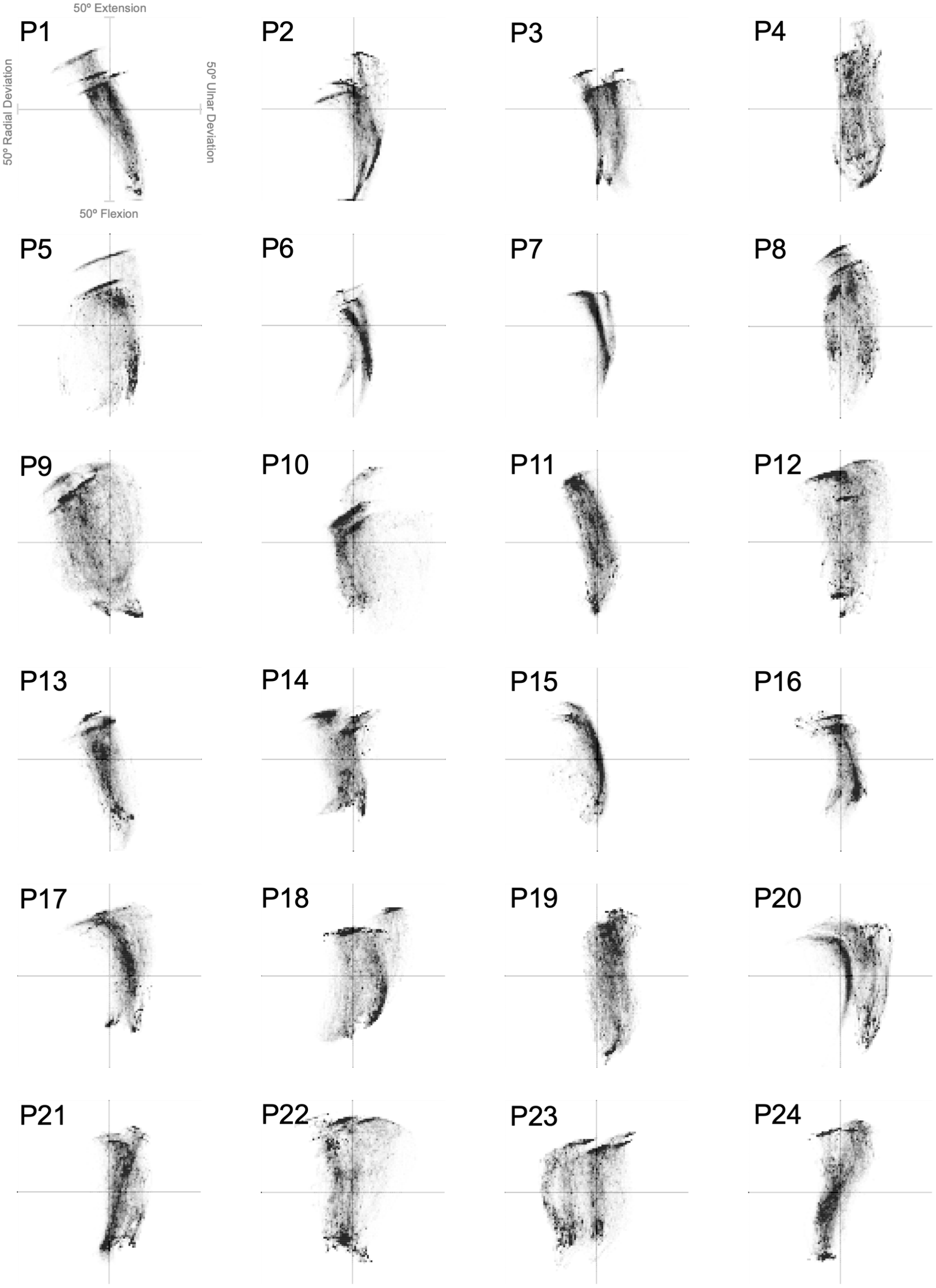

Figure 10: All 24 participants' density plots for 2D wrist angles across all tasks and postures with both wrist deflection techniques (multiple sessions with different calibrations). The graph's axes are analogous to the motion of the right wrist when viewed from a first-person perspective (i.e., down and up are flexion and extension respectively, left and right and radial and ulnar deviation). The ideal behavior is a perfect vertical line indicating that the user's hand only moves along flexion-extension without any deviation, but many participants demonstrated curved or tilted paths instead.