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NURing: A Tendon-Driven Wearable Ring for On-Demand Kinesthetic Haptic Feedback

Tomasz P. Trzpit
Department of Mechanical Engineering
Northwestern University
Evanston, IL, USA
ttrzpit@u.northwestern.edu

Gregory Reardon
Department of Mechanical Engineering
Northwestern University
Evanston, IL, USA
gregory.reardon@northwestern.edu

Anthony Shilati
Department of Mechanical Engineering
Northwestern University
Evanston, IL, USA
anthonyShilati2029@u.northwestern.edu

Elizabeth M. Gerber
Segal Design Institute
Northwestern University
Evanston, IL, USA
egerber@northwestern.edu

Michael A. Peshkin
Department of Mechanical Engineering
Northwestern University
Evanston, IL, USA
peshkin@northwestern.edu

J. Edward Colgate
Department of Mechanical Engineering
Northwestern University
Evanston, IL, USA
colgate@northwestern.edu

***Abstract*—Generating salient and intuitively understood haptic feedback on the human finger through a non-intrusive wearable remains a challenge in haptic device development. Most existing solutions either restrict the hand and finger's natural range of motion or impede sensory perception, quickly becoming intrusive during dexterous manipulation tasks. Here, we introduce NURing (Non-intrUsive Ring), a tendon-actuated haptic device that provides kinesthetic feedback by deflecting the finger. The NURing is easily donned and doffed, enabling on-demand kinesthetic feedback while leaving the hand and fingers free for dexterous tasks. We demonstrate that the device delivers perceptually salient feedback and evaluate its performance through a series of uniaxial motion guidance tasks. The lightweight NURing device, measuring approximately 220 g, can generate guidance cues at up to 1 Hz, enabling participants to identify target directions in under 3 s with a 1.5° steady-state error, corresponding to a fingertip deviation of less than 11 mm. Additionally, it can guide users along complex, smooth trajectories with an average trajectory error of 7°. These findings highlight the effectiveness of fingertip deflection as a kinesthetic feedback modality, enabling precise guidance for real-world applications such as sightless touchscreen navigation, assistive technology, and both industrial and consumer augmented/virtual reality systems.**

***Index Terms*—Wearable Haptics, Kinesthetic Feedback, Haptic Device, Motion Guidance, User Studies**

I. Introduction

Wearable haptic devices have the potential to augment the body's natural sensory and motor capabilities. Devices worn on the hand or arm, in particular, attempt to leverage the evolutionarily refined senses of touch and proprioception, aiming to generate tactile and kinesthetic cues that can be readily perceived and acted upon with minimal effort. Enhancing the natural salience and intuitiveness of these cues remains a challenge but holds the promise of unlocking new and enhancing current forms of interactions in a myriad of domains ranging from assistive technologies, industrial augmented reality, consumer augmented reality, and virtual reality (Fig. 1A).

This work focuses specifically on the generation of guidance cues in the peripersonal space by means of a wearable, non-grounded device. This particular interaction task—guidance cues in a wearable modality—has been the subject of much interest by researchers, both for use in assistive technology for the visually-impaired or for motor task learning [1], [2], [3]. A majority of the devices designed to address this task rely on imparting tactile stimuli to the user through skin surface sensations. Some devices use haptic actuators (tactors) to generate vibrotactile stimuli that are then interpreted by the wearer as a guidance cue. For hand-worn devices, these stimuli can be applied to individual fingers [4], [5] or distributed across the entire hand or arm [6], [7], [8]. Other devices utilize complex mechanisms to generate tactile skin-stretch stimuli to the fingers [9] or the arm [10], or incorporate non-standard actuation techniques, such as electrical muscle stimulation, to induce non-volitional movement [11].

While a majority of wearable haptic devices focus on tactile feedback, recently there have been several promising developments in rendering kinesthetic feedback. Most of these devices generate forces by reacting against the body (non-grounded) [12]. Another approach is to incorporate soft pneumatic muscles woven into a glove that are actuated to generate fingertip movement [13]. Hybrid tactile/kinesthetic devices have also been developed, combining cutaneous fingertip feedback with a wearable kinesthetic exoskeleton [14]. Commercial hybrid devices such as the HaptX Gloves and the SenseGlove are also available, but these typically focus on facilitating haptic interactions in virtual or teleoperation settings rather than real-world interactions in the peripersonal space.

Though promising, wearable guidance devices continue to face a range of challenges that have limited their broader adoption and practical deployment. For example, while vibrotactile devices are fairly easy to implement (in terms of actuation),

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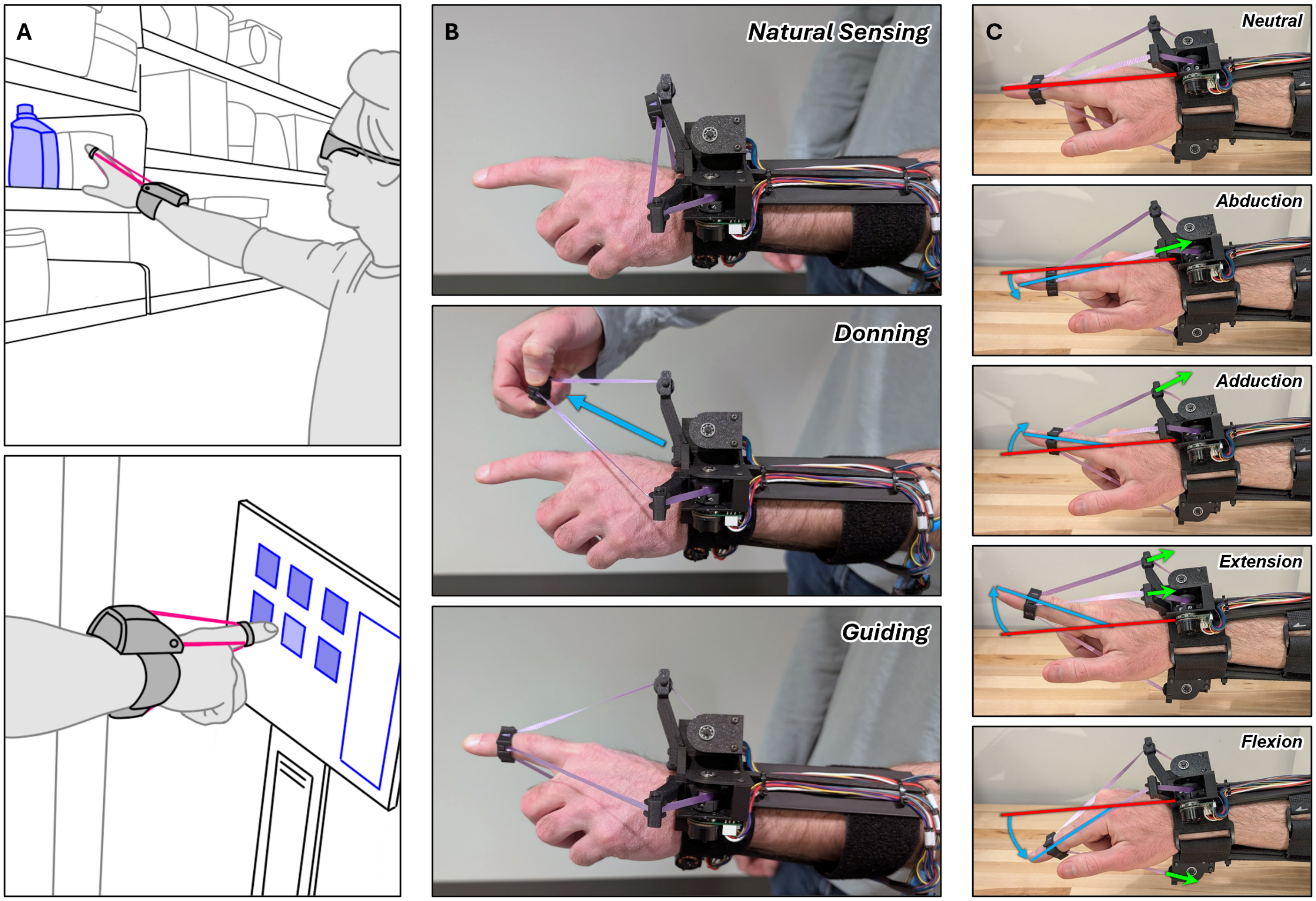

Fig. 1. **NURing: Non-IntrUsive Ring for On-Demand Kinesthetic Feedback**. A) Concept art illustrating how the NURing can be used to aid a wide range of manual tasks such as those found in industrial augmented reality (top) or as an assistive device for individuals with visual impairment (bottom). B) The NURing is easy to don and doff, providing on-demand kinesthetic feedback without restricting a users' range-of-motion or impeding natural touch sensing. C) The NURing is capable of delivering two-dimensional kinesthetic feedback by deflecting the finger using a tendon-driven ring.

they often require extensive training by the user to correctly interpret the vibrational cues [15], [16]. Furthermore, in tasks where external vibrations are present, or when the user is not actively monitoring for cues, vibrotactile cues may fail to reach the vibration perception threshold and go unnoticed by the user [17]. Conversely, while electrotactile devices can provide strong physical cues, they are sensitive to local skin conditions and require individualized calibration as sensory thresholds can vary [18]. Mechanical kinesthetic feedback devices offer the ability to impart significantly stronger forces upon the wearer, but often at the cost of increased mechanical complexity and bulk [1], [19].

Moreover, the very nature of the device being wearable introduces several challenges. Thimble- and glove-based devices can potentially obscure the finger pad, leading to a loss of cutaneous feedback [20]. Stronger kinesthetic devices are often dependent on rigid, mechanical linkages that would make them intrusive to dexterous manipulation tasks or impede a user's range of motion [1]. Those that utilize pneumatics may be tethered to external air supplies, limiting their portability and application in daily tasks.

To address these limitations, we introduce the NURing (Non-IntrUsive Ring), a wearable device that combines a wrist-worn driving band with a tendon-actuated retractable ring. The NURing imparts kinesthetic cues on the index finger through deflection, taking advantage of the earliest recognizable gesture that we learn as children—that of pointing towards a desired object [21]. By having the actuation point be deployable "on-demand", the device can be worn continuously without interfering with dexterous tasks (Fig. 1B, top). When guidance cues are required, the ring can be pulled from the wrist device (Fig. 1B, middle), extending the tendons to the length of the finger. Once the ring is placed upon the finger, tension is applied to keep the ring in place (Fig. 1B, bottom). When guidance is complete, the ring can be pulled off of the finger and retracted back towards the wrist-worn driving band (Fig. 1B, top).

In the remainder of the paper, we detail the NURing and then demonstrate its capabilities to generate natural motion guidance

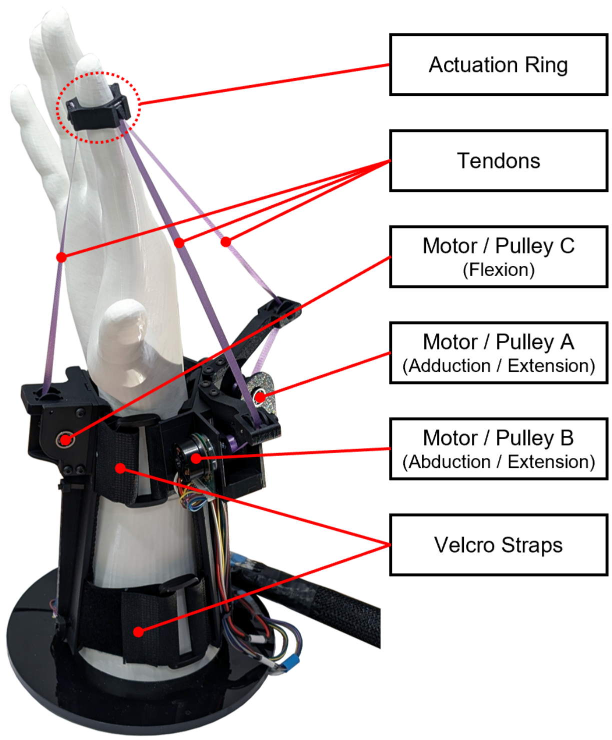

Fig. 2. **Components of the NURing Wearable Device.** The NURing device consists of three tendon-driven motors that apply forces to the actuation ring. The ring sits on the middle phalanx of users, just above the proximal interphalangeal (PIP) joint. Forces applied at the actuation point cause torques about the metacarpophalangeal (MCP) joint, deflecting the finger along two axes. The entire system is fixed to the user's arm via adjustable Velcro straps.

cues in a user study that consisted of three uniaxial tasks—open-loop motion cues, single-direction guidance, and trajectory tracking. In the study, we found that the NURing generated perceptually salient and interpretable motion cues. Participants were readily able to perceive and respond to finger deflection cues at frequencies up to 1 Hz, move their arm to within 1.5° of a target direction (i.e., $<$ 11 mm fingertip deviation for a 40 cm reach) in under 3 s, and follow complex trajectories with a 7° tracking error. Critically, this was all performed without prior training and with minimal exposure to the NURing. These results demonstrate the device's potential to support real-time, eyes-free tasks such as touchscreen navigation, object localization, and trajectory following in assistive, industrial, or AR/VR applications. The user study methodology is detailed in Sec. III, while the user study results are presented in Sec. IV. We conclude with a discussion of the motion guidance results (Sec. V) and future work (Sec. VI).

II. The NURing Testbed

The NURing induces lateral deflection of the index finger by applying a combination of lateral and vertical forces to the middle phalanx, yielding a torque about the metacarpophalangeal (MCP) joint (Fig. 1C). The device consists of two wearable elements: a wrist-mounted drive band and a ring worn upon the middle phalange of the index finger that serves as an actuation point (Fig. 2). Here, we present the wearable device and the experimental platform, which comprise the NURing Testbed.

A. Kinesthetic Guidance Device

We used three actuators to fully actuate the finger in four directions of deflection (abduction, adduction, extension, flexion). These actuators are mounted on the drive band, which consists of an upper and lower component. The upper component contains two 22 mm brushless DC motors (Maxon ECX Flat 22 L), and the lower component contains a single motor of the same type. The upper motors (motors A and B) provide pulling forces towards adduction/extension and abduction/extension (respectively), and the lower motor (motor C) provides a pulling force towards flexion.

While the device is capable of generating 2D guidance cues for navigation in three-dimensional space, the tasks presented in this work are constrained to the horizontal plane (i.e., finger abduction/adduction). Given the positions of the tendons, when a pure lateral motion is desired, the appropriate abduction/adduction motor is used on the top of the drive band, coupled with a complementary force in the direction of flexure from the bottom of the drive band, to offset the vertical pull of the top platform motors.

Each motor is driven by a BLDC amplifier (Copley Controls Nano NES-090-10-Z), housed on an external base station, separate from the wearable, to facilitate device development (Fig. 3). These amplifiers provide current-based torque control, providing a nominal torque of 28.3 mN·m at 1.89 A. Coupled with 6-mm diameter pulleys driven by the motors, each actuator is capable of pulling up to 9.43 N of force (at nominal current levels). In addition to driving the motors, the amplifiers also incorporate feedback from motor-integrated 1024 CPT incremental encoders (Maxon ENX 22 MILE). The amplifiers interface over a wired RS-232 serial connection with a microcontroller (PRJC Teensy 4.1; also located on the base station). This interface allows for the sending of a 1000 Hz, 12-bit PWM drive signal that corresponds to a commanded current (I_{A_c}, I_{B_c}, I_{C_c}), and the receipt of motor encoder counts (which are then converted to motor angles ϕ_A, ϕ_B, ϕ_C) and measured motor current (I_{A_m}, I_{B_m}, I_{C_m}).

These motors/amplifiers are used to each pull upon an inextensible, lightweight polyester ribbon that acts as a tendon. When compared with traditional cables, we found the ribbon-based tendons to be less prone to tangling during donning and doffing and produced minimal discomfort in circumstances when the actuated tendon rubbed against the user's skin. The drive band itself is affixed to the user's arm at two points (around the wrist and around the forearm) via 50 mm-wide adjustable Velcro straps to constrain the device and maintain alignment with the index finger. The ribbon-based tendons are attached to an actuation ring which translates motor forces into finger deflections (Fig. 2). We 3D printed the actuation ring in a variety of sizes to comfortably fit the fingers of different users. The iteration of the ring presented in this paper utilizes attachment points that allow for the tendons to be detached

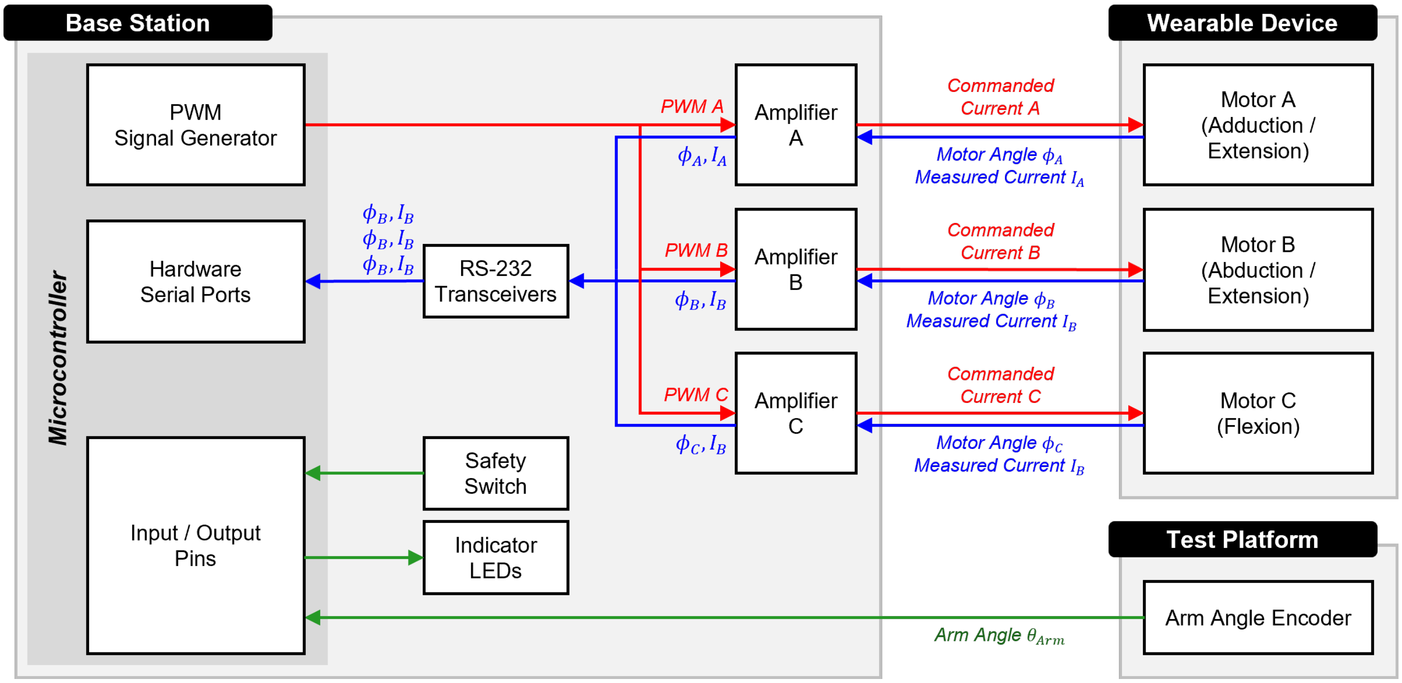

Fig. 3. **NURing Testbed system architecture.** The base station (left panel) is responsible for coordinating the interactions between the different testbed components. Motor current values are commanded via a 12-bit PWM signal, and actual motor currents are measured by the amplifier and sent back to the microcontroller via RS-232 serial, along with measured motor angles from the wearable device (top right panel). The forearm angle encoder (bottom right panel) is measured on interrupts and is used to provide open-loop measurements during task 1, and closed-loop feedback during tasks 2 and 3.

from the ring to facilitate user studies. These attachment points are defined relative to a hand held flat with fingers extended, palm facing downward. Two tendons are mounted at 35° above the plane of the hand (i.e., the coronal plane), one positioned laterally and the other medially relative to the wrist. A third tendon is mounted beneath the coronal plane, aligning with the base of the index finger. The position of the top two motors and attachment points was biased vertically up towards the direction of finger extension to induce a greater moment arm, ensuring that the finger is deflected up towards extension rather than being pulled straight back towards the MCP joint. Conversely, as passive finger stiffness is far lower in flexion than extension, pulling on the finger at the middle phalange induces a curling motion downward rather than buckling inward towards the MCP joint. This allows for the use of a single motor for flexion without the need for an extended moment arm.

A key goal in the development of this system was to allow the guidance cues to be provided “on-demand”, meaning that when kinesthetic guidance is not needed, the device should remain out of the way and not interfere with other dexterous manipulation tasks. To aid this, during operation, the motors constantly supply a small torque to maintain tension on the ring and hold it in place. When the guidance cues are no longer needed, the ring is then removed from the finger, and the tensioning torque pulls on the tendons and retracts the ring back into the drive platform. Alternatively, the individual tendons can be detached from the ring and retracted back into the actuation platform, allowing for interoperability among users with different ring sizes. The overall mass of the drive platform, as presented in this paper, is approximately 220 g, similar to that of a smartphone.

The base station that houses the amplifiers also includes a microcontroller (PJRC Teensy 4.1) that sends command signals to the motor amplifiers, manages sensor feedback from the motor encoders and the experimental platform arm encoder (see below), and drives support electronics (such as LED indicators). The base station also accommodates the necessary power supplies and regulators (Fig. 3).

B. Control Methods

We implemented a classical proportional controller to generate closed-loop kinesthetic cues. In the two closed-loop control tasks (task 2 and task 3), the measured arm angle (captured by the experimental platform, defined below) is compared to the desired angle, and the difference is multiplied by a gain K_P to provide a guidance command. This command is then processed and split between the three BLDC motors to drive a commanded torque. The maximum torque produced by the BLDC motors was limited in firmware to 28.3 mN·m, which was found through experimentation to be strong enough to deflect the user’s finger but still weak enough to allow the user to overcome the torque if needed.

C. Experimental Platform

We designed a controlled experimental platform to perform user studies and assess how users responded to the kinesthetic cues provided by the NURing (Fig. 4A). This platform consists

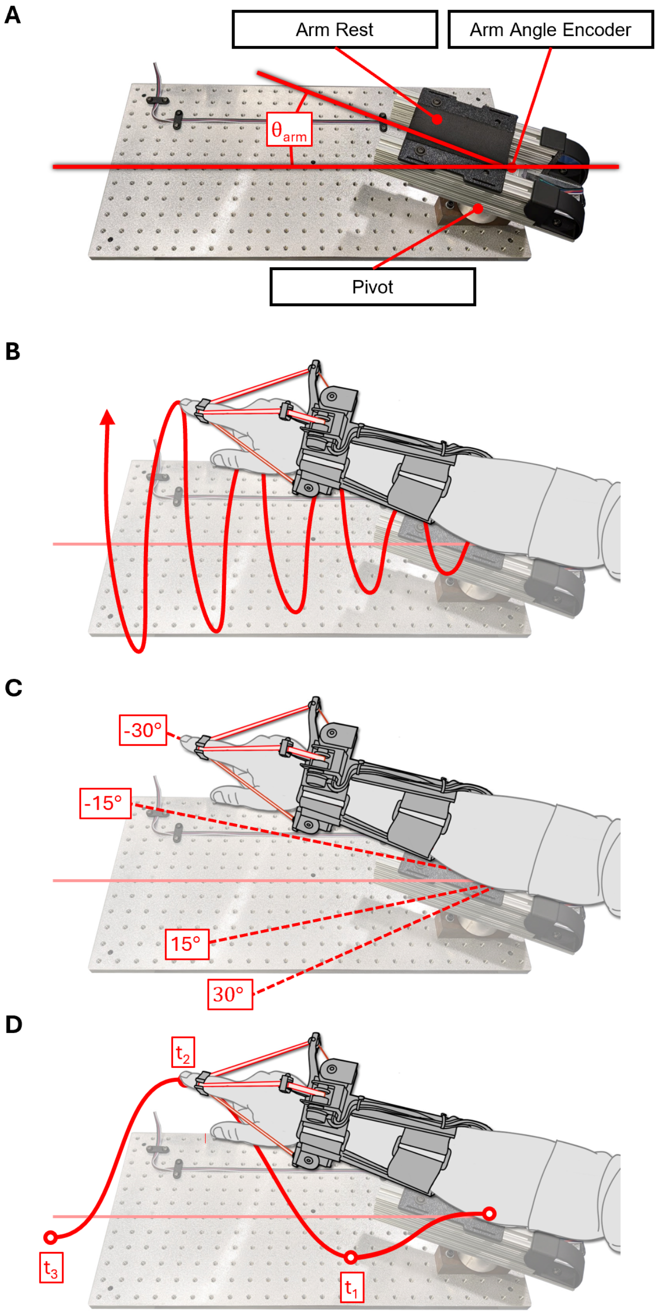

Fig. 4. **Experimental platform for performing user studies.** A) The experimental platform consists of an armrest, a pivot, and an internal encoder used to measure the participant's forearm angle θ_{arm} in response to finger deflection cues delivered by the NURing. B) In task 1 (open-loop motion cues), participants responded to sinusoidal motion cues delivered by the NURing. C) In task 2 (single-direction guidance), the NURing guided participants to one of four possible target angles $\theta_{\mathrm{t}} = -30°, -15°, 15°, 30°$ using closed-loop control. D) In task 3: trajectory tracking, the NURing guided participants along a target trajectory $\theta_{\mathrm{t}}[n]$ using closed-loop control. Example two-reversal trajectory shown.

of an armrest mounted on a pivot, coupled with an incremental encoder (CUI Devices AMT102) used to measure the angle of the subject arm (θ_{arm}). This angle is computed by the microcontroller and used to measure responses to kinesthetic cues in open-loop trials and to provide closed-loop feedback in single-direction guidance and trajectory tracking tasks (see also Fig. 3).

III. Methods: User Study

We conducted a user study on our controlled experimental platform in order to assess the capabilities of the device for generating lateral motion cues and guidance in the peripersonal space. The study consisted of an initial range of motion characterization (Sec. III-A), followed by an open-loop motion task (Sec. III-B) and two closed-loop tasks: single-direction guidance (Sec. III-C) and trajectory tracking (Sec. III-D). After the study, participants completed a 6-question Likert survey and a series of open-ended questions aimed at assessing the usability of the device (Sec. III-E). The protocol was approved by the human subjects review board at the authors' institution. The study took approximately one hour to complete. One participant was removed from the study for repeatedly ignoring the experimenter's instructions regarding proper device and experimental platform use, yielding a total of eight participants who completed the study (ages 22 to 46, 3 female, 5 male). All participants in the study gave their written, informed consent and were compensated $15 for their time.

In each of the three tasks, participants felt cues delivered to the index finger of their right hand and were instructed to respond to the cues by rotating their arm on the experimental platform about the elbow (i.e., one-axis motion). Similar to Satpute et al. [4], participants were blindfolded during the experimental trials. Participants also wore noise-canceling, circumaural headphones to mask auditory cues. Before the experimental trials, participants engaged in a sighted (non-blindfolded) familiarization phase that allowed them to become comfortable with the cues that would be delivered by the device. During familiarization, participants were never instructed whether their responses were "accurate" or "correct." Participants' arms were supported on the experimental platform with their elbow placed directly about the platform pivot point and in a neutral position ($\approx 90°$ angle between forearm and upper arm). An encoder on the pivot point captured the participant's forearm angle, θ_{arm} (Fig. 4A). Data from the encoder was synchronously captured with data from the NURing (i.e., motor currents), and data regarding the experimental trial (i.e, the motion cue) at a rate of 100–200 Hz. In the closed-loop control tasks, the measured forearm angle, θ_{arm}, was used to modulate the NURing kinesthetic feedback in real time to guide users to specified directions or along specified trajectories.

A. Device Personalization

At the beginning of the study, participants first selected a NURing that sat comfortably on the middle phalanx just above the proximal interphalangeal joint (PIP). The device was attached to the participant's right arm using Velcro straps, and the central longitudinal axis of the device was aligned with the participant's index finger. Next, participants were instructed to draw a circle in the air with their finger while we recorded motor encoder positions, allowing us to set limits on the NURing motor currents to ensure participants' fingers were never pulled beyond their normal range of motion.

B. Task 1: Open-Loop Motion Cues

Task 1 assessed participants' responses to sinusoidal motion cues of varying frequency delivered by the NURing (Fig. 4B), resulting in an open loop frequency response. In each trial, the finger was deflected sinusoidally in the lateral direction at one of five frequencies, $\mathbf{f} = 0.25$, 0.33, 0.5, 1, and 2 Hz, for 5 cycles, and participants moved their arm to align with the deflected finger. The sinusoid amplitude was set to the participants' maximum range of motion, which was measured during the range-of-motion characterization. Each frequency was presented 3 times in a block-randomized fashion for a total of 15 trials per participant (5 frequencies x 3 repetitions). After completing a trial, participants were instructed by the experimenter to return to a neutral position. During the familiarization phase, participants were asked to explore moving their forearm with the experimental platform, go through a full elbow range of motion, and experienced the lowest and highest frequency (f = 0.25 and 2 Hz) that would be presented.

C. Task 2: Single-Direction Guidance

Task 2 assessed the capability of the NURing to guide participants to a target forearm angle, θ_t, as quickly and accurately as possible (Fig. 4C). Here, we hypothesized that the finger's refined sensing capability would allow it to respond to deflection cues with high precision, guiding the whole arm towards the desired target angle. Motion cues were delivered through the NURing in a closed-loop fashion to achieve the task as fast and as accurately as possible. At the target forearm angle, the NURing provided no kinesthetic feedback, which indicated to participants that they had achieved the task. In each trial, participants were guided to one of four angles, $\theta_t = -30°, -15°, 15°$, and $30°$ (with respect to their neutral position, with negative indicating an adduction cue), at one of five proportional controller gains, K_p = 2.0, 2.5, 3.0, 3.5, 4.0 (see Sec. II-B). Each condition was repeated once per participant in a fully randomized fashion for a total of 20 trials per participant (4 θ_t x 5 K_p). Participants were instructed to try to move their forearm to align with the intent of the device and to pause and remain still after they were satisfied that they were pointed in the target direction. The trial length was fixed at 6 s, with the cue being delivered after 0.5 s, implying some participants did not complete the task in the allotted 5.5 s (i.e., pause after they were satisfied with their response), though the trial was still counted for analysis purposes. After completing the trial, participants were instructed to return to a neutral position. During the familiarization phase, participants felt random target directions (that were not tested in the task) at different gains to understand the intent of the task.

D. Task 3: Trajectory Tracking

Task 3 assessed the NURing's ability to guide participants along specified trajectories (Fig. 4D). We hypothesized that the participant would be able to react to changes in deflection cue direction in real-time, allowing for tracking of a moving target. Motion cues were delivered in a closed-loop fashion, with the NURing providing feedback when participants deviated from the target trajectory. We set the controller gain in the task heuristically based on observing the participants' response trajectories and their empirically measured errors from task 2. Participants were tasked with tracking the target trajectory by adjusting their forearm angle. Target trajectories, $\theta_t[n]$, were constructed by combining multiple Bézier curves. We varied the path complexity (i.e., the number of reversals or Bézier curves constructing the trajectory) and the path speed. Path complexity varied from a one-reversal trajectory to a three-reversal trajectory, and each complexity type had 3 trajectories for a total of 9 different trajectories tested. We also varied the speed at which these trajectories completed between 4, 8, and 12 s (denoted as "fast", "medium", and "slow" in the proceeding analysis). This yielded a total of 27 experimental stimuli, each of which was presented for 3 repetitions in a block-randomized fashion. Each participant thus completed a total of 81 trials in this task. We ensured a balance of trajectories that began moving with positive and negative target angles (i.e., 5 abduction first and 4 adduction first). After the trial was completed, participants were instructed to return to neutral for the next trial. During the familiarization phase, participants felt one trajectory from each trajectory class that was presented at different speeds in both sighted and blindfolded conditions (18 total familiarization trials). The curves used in the familiarization phase were not used in the experimental trials.

E. Post-Study Survey

After completing the three tasks, participants assessed the "Comfortability," "Interpretability," "Naturalness," "Confidence," "Satisfaction," and "Mental Effort" of the motion guidance cues in a 7-point Likert survey from "Strongly disagree" to "Strongly agree." The survey questions were provided in an alternating positive/negative valance form and were as follows:

- **Comfortability**: The guidance cues provided by the device were comfortable to experience.
- **Interpretability**: The guidance cues provided by the device were unclear and challenging to interpret.
- **Naturalness**: The guidance cues provided by the device felt natural and intuitive.
- **Confidence**: I felt unsure and not confident following the guidance cues provided by the device.
- **Satisfaction**: I was satisfied with the performance of the haptic device for providing motion guidance cues.
- **Mental Effort**: The guidance cues provided by the device required a lot of mental effort to follow.

For simplicity of presentation, the data from the negative valence questions was inverted such that all survey results are interpreted with respect to positive valence.

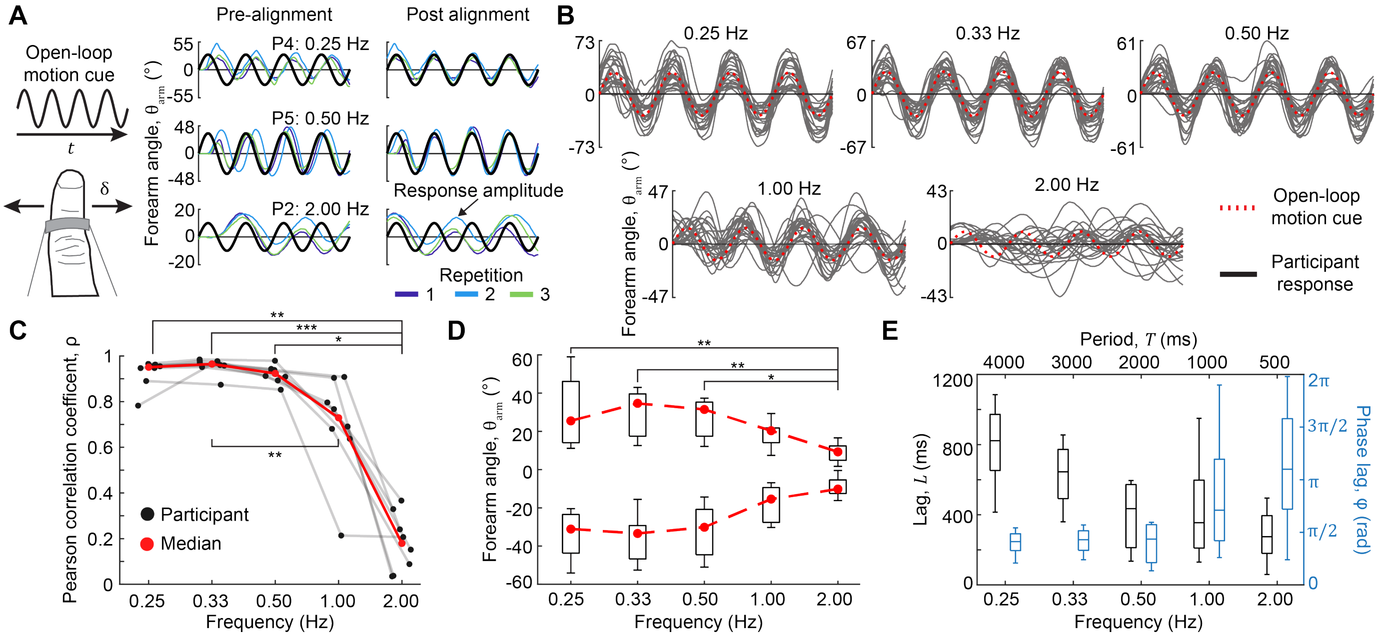

Fig. 5. **Results of task 1: open-loop motion cues.** A) Participants received sinusoidal motion cues delivered by the NURing and responded by adjusting their forearm angle (left panel). Selected participant responses (colored lines) to sinusoidal motion cues (black line) at three selected frequencies $f = 0.25$, 0.5, and 2.0 Hz and participants before (center panel) and after (right panel) cross-correlation alignment (i.e., phase alignment). B) Phase-aligned responses for all participants and all trials (black traces) with the sinusoidal motion cue overlaid (dashed red line). C) Participant distributions of Pearson correlation coefficients, ρ, calculated from the phase-aligned responses. Block dots and lines: participant responses; red dots: median of participant responses; *,**,***: significance of $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively. D) Boxplots of the amplitude of participants' sinusoidal motion responses. Box limits: lower and upper quartiles; red dot and lines: median; whiskers: distribution extrema; *,**: significance of $p < 0.05$ and $p < 0.01$, respectively. E) Boxplots of the optimal lags used for trial alignment. Lag was computed in both milliseconds (black boxplots) and radians (i.e., normalized by the sinusoid period, T; blue boxplots). Box limits: lower and upper quartiles; center line: median; whiskers: distribution extrema.

F. Statistical Analysis

Thresholds for statistical significance were set at three levels: $\alpha < 0.05$, $\alpha < 0.01$, and $\alpha < 0.001$, with significance below threshold denoted with *, **, and ***, respectively. Given the prevalence of outliers in our experimental results, all data was statistically analyzed using non-parametric Friedman tests. In the case of significance, follow-up (pairwise) Wilcoxon signed-rank tests with a Bonferroni correction were used to assess differences between individual groups.

IV. Results: User Study

A. Task 1: Open-Loop Motion Results

The NURing was able to provide highly salient and interpretable feedback to participants with no prior training. In response to sinusoidal motion cues, participants responded with sinusoidal motion paths with an average response amplitude of 22.1° and –23.9° over all experimental trials (Fig. 5A, all trials for three different participants at select frequencies shown).

We computed the lag between the input signal (i.e., the cue) and the participant response via cross-correlation and aligned all experimental trials. We allowed a lag of up to 1 cycle of the sinusoid and analyzed the first 4 cycles of the phase-aligned responses (Fig. 5B). The response paths exhibited a median lag of 472.5 ms over all trials. At frequencies below 1 Hz, the responses were highly consistent over multiple repetitions and across subjects (Fig. 5B). At frequencies above 1 Hz, participants were unable to fully complete a cycle of movement about neutral before the next cycle of the cue was delivered, yielding inconsistent responses.

We also computed the Pearson correlation coefficient, ρ, between the input and output signals averaged across repetitions and sinusoid cycle. The correlation coefficient decreased rapidly as frequencies approached and exceeded 1 Hz (Fig. 5C). The median Pearson correlation across participants reached as high as 0.96 after phase alignment and reached as low as 0.18 at 2 Hz, reflecting the inability of participants to respond to motion cues at these high frequencies. We used a Friedman test on the resulting distributions with "Frequency" as our factor and found a significant decrease in ρ as frequency increased ($p < 0.001$***, $\chi^2(4, N = 8) = 27.7$). Follow-up pairwise Wilcoxon signed-rank tests indicated significant differences between 0.25 and 2 Hz ($p = 0.003$**), 0.33 and 1 Hz ($p = 0.009$**), 0.33 and 2 Hz ($p < 0.001$***), and 0.5 and 2 Hz ($p = 0.04$*). All other groupings were not significant.

We then assessed whether there were differences between the amplitudes of the participants' sinusoidal responses by computing the maximum and minimum amplitude of the response for each cycle (Fig. 5D). Responses were once again averaged across repetitions and cycles, and Friedman tests were used to assess both the effect of frequency on motion amplitude and whether participants favored abduction

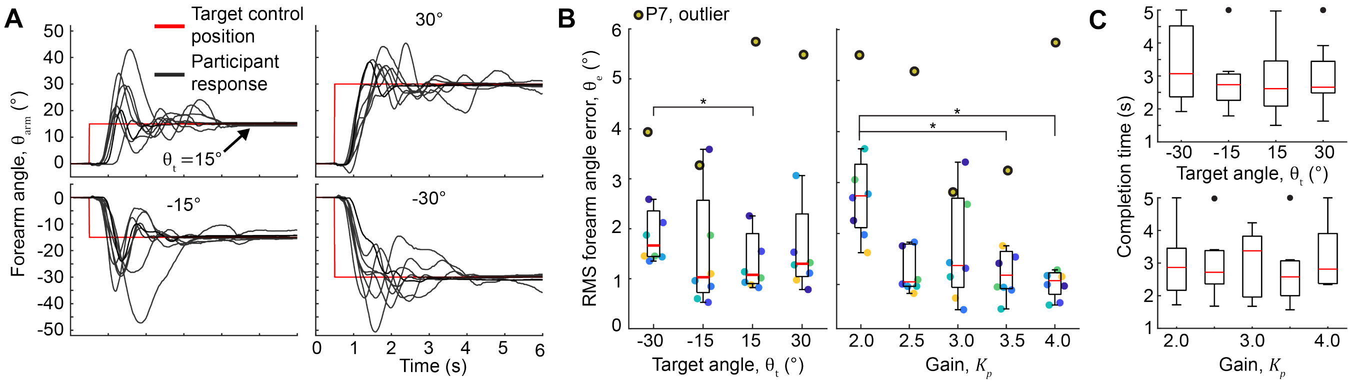

Fig. 6. **Results of task 2: single-direction guidance.** A) The NURing delivered motion cues to guide participants to a target forearm angle. Participant forearm angles (black) in response to the motion with the target direction overlaid (red). For each angle, one trial from each participant is shown and selected based on their "best" trial (i.e., lowest RMS forearm angle error at the end of the trial). B) Boxplots and scatter plots of participant RMS forearm angle error at the end of the trial as functions of the experimental variables—target direction and control gain K_p. P7 was identified as an outlier and removed from the distributions for statistical analysis. Box limits: interquartile range (IQR); red center lines: median, whiskers: 1.5x IQR or distribution extrema if within 1.5x IQR; colored dots: participants median error across three repetitions coded by color; *: significance of $p < 0.05$. C) Boxplots of participant task completion times as a function of the experimental variables. Box limits: IQR; red center line: median; whiskers: 1.5x IQR or distribution extrema if within 1.5x IQR; black dots: outliers.

or adduction ("Direction"). For the former, the per-participant maximum and minimum amplitudes were averaged after taking the absolute value. For the latter, participant data across frequencies was averaged, and the absolute value of the amplitudes was taken. We found a significant effect of "Frequency" on the response amplitude (Friedman test; $p < 0.001$***, $\chi^2(4, N = 8) = 19.09$). Significant differences between 0.25 and 2.0 Hz ($p = 0.002$**), 0.33 and 2.0 Hz ($p = 0.004$**), and 0.5 and 2.0 Hz ($p = 0.04$*) were found in the follow-up Wilcoxon signed-rank tests. All other groupings were not significant. We found no significant effect of "Direction" on the amplitude of the responses, indicating participants could easily respond in both directions about neutral throughout the study and did not favor either abduction or adduction.

Finally, we performed an analysis of the input-output lags that were used to align our experimental trials. We took the average input-output lag, L, across repetition and sinusoid cycle, yielding distributions of lag in milliseconds, and also computed this lag with respect to the sinusoid period, T, yielding phase lag, ϕ, in radians (Fig. 5E). We found that L was not constant across input frequency. However, ϕ was highly consistent across the three lowest frequencies for which participants performed exceedingly well ($f = 0.25, 0.33, 0.5$ Hz). At higher frequencies ($\geq$1 Hz), ϕ was distributed across a wide range of values. Thus, at high frequencies, lag appears more closely related to participants' reaction time rather than the content of the motion cue. To assess whether L or ϕ was a better predictor of the participants' responses to the open-loop motion cues, we restricted the data to the lowest three frequencies and conducted Friedman tests using both outcome variables. We found a significant effect of frequency on L ($p < 0.001$***, $\chi^2(2, N = 8) = 16$), but no significant effect on ϕ. These results suggest that participants respond, when physically able to, to sinusoidal motion cues with a phase lag, ϕ of approximately $2\pi/5$ rad (i.e., 72°). This stable phase relationship indicates that, at lower frequencies, user response timing remains consistent and predictable, providing a reliable basis for modeling user response in guidance interactions.

B. *Task 2: Single-Direction Guidance Results*

In the single-direction guidance task, participants were able to complete the task (i.e., reach a steady state and pause before 5 seconds after the cue was first applied) in over 88% of trials (141 / 160 trials), with an average completion time of 2.79 s (Fig. 6A). 13 of the 19 trial failures were attributed to a single participant (P7) and no other participant failed more than one trial. Participants nearly universally overshot the target direction. The average initial overshoot across all experimental trials, computed as the angle error between the target θ_t and response θ_{arm} at the participants' first reversal of their motion direction, was 10.44°. For the proceeding analysis, participants who did not complete the task were given the max completion time of 5 s, and their error was computed as the root mean square (RMS) error for the last 1 s of the trial.

To assess the steady-state error (and the completion time), we used an offset detection algorithm based on the response derivative to identify the time at which participants stopped moving their arm and were thereby satisfied with their response direction. This was necessary as slight arm movements were present even after participants "completed" the task. We treated the participant response after this offset time as the steady-state response signal, subtracted the target direction θ_t from this signal, and computed the RMS to yield the response error, θ_e. The median response error across all experimental trials was 1.45°, indicating that participants were extremely successful in finding the target direction (Fig. 6B). We also assessed response error as a function of the target direction and the control gain, K_p, using Friedman tests. For the purposes of statistical analysis, we removed one participant who was an

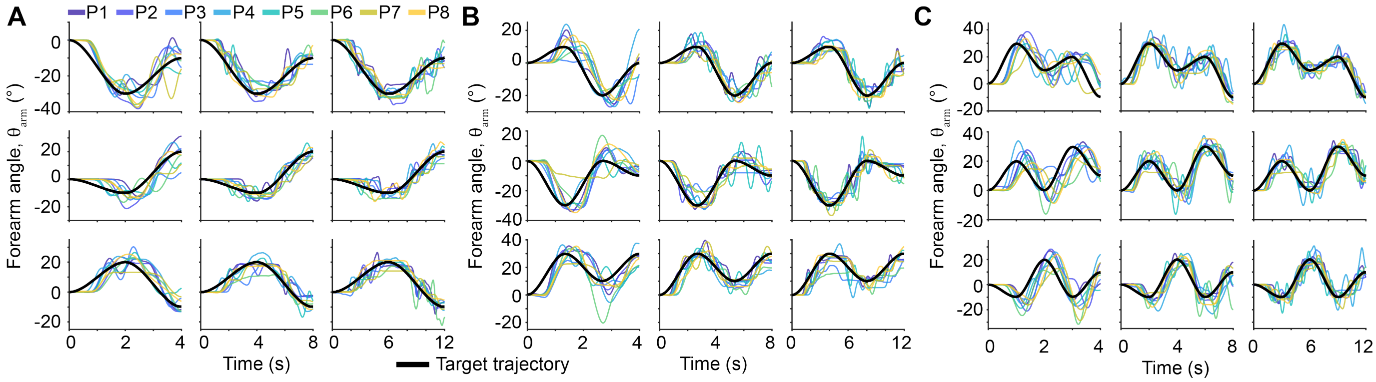

Fig. 7. **Results of task 3: trajectory tracking.** Participants tracked a curved trajectory that had a single reversal (A), two reversals (B), or three reversals (C) with the NURing. Black line: target trajectory; colored lines: participant responses coded by color. Participants' "best" trajectory (i.e., lowest RMS angle error between the target trajectory and the response trajectory) for a given path complexity and trajectory speed is shown.

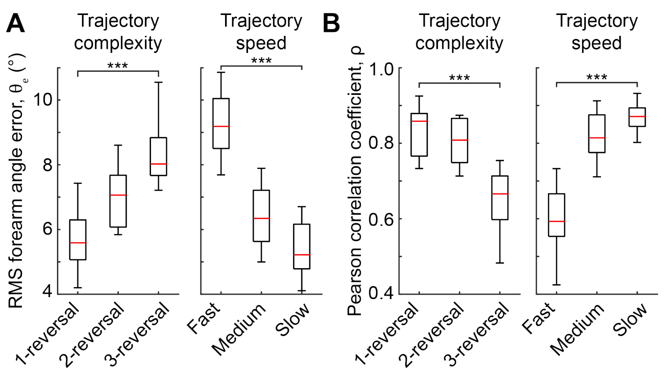

Fig. 8. **Summary results of task 3: trajectory tracking.** Boxplots of the RMS angle error (A) and Pearson correlation coefficient, ρ, (A) between the target trajectory and participants' response trajectories. For both metrics, the median was taken over participant repetition and then averaged over the remaining dimensions. Box limits: interquartile range; red center line: median; whiskers: distribution extrema; ***: significance of $p < 0.001$.

outlier (Fig. 6B, P7); this participant was the same one who failed to complete 13 of their trials. We found a significant effect of target direction θ_t on the response errors θ_e ($p = 0.037$*, $\chi^2(3, N = 7) = 8.49$). In follow-up Wilcoxon signed-rank tests, participant performance for target angle θ_t = –30° was significantly worse than for target angle θ_t = 15° ($p = 0.02$*). We also found a significant effect of control gain, K_p, on the response error, θ_e ($p = 0.02$*, $\chi^2(4, N = 7) = 11.66$). The results of Wilcoxon signed-rank tests indicated that participant performance with gain K_p = 2.0 was significantly worse than with gain K_p = 3.5 ($p = 0.04$*) or K_p = 4.0 ($p = 0.04$*). Thus, participants performed nearly equally well for all but the lowest control gain. Finally, we computed participant distributions for completion time (Fig. 6C). Friedman tests indicated that neither "Angle" nor "Gain" had a significant effect on the trial completion time.

Together, these results indicate that the NURing is highly effective at guiding participants to the target direction both rapidly (< 3 s on average) and accurately (< 1.5° error on average). For a 40 cm reach (as measured from the elbow), a 1.5° direction error corresponds to a fingertip deviation of < 11 mm from a target location. This suggests that NURing may be used to guide the hand to coin-sized objects (e.g. buttons on a touch screen) in peripersonal space.

C. Task 3: Trajectory Tracking Results

In the final task, participants were charged with tracking various smooth trajectories using the NURing (Fig. 7A, B, C). Participant responses were more varied than in the other tasks, reflecting the relative difficulty of the task when compared with the others. Generally, the paths were followed exceptionally well, with an average RMS forearm angle error of 7.02° and an average Pearson correlation coefficient of 0.76. The results were not phase-aligned, though many responses appeared to lag a few hundred milliseconds behind the path (Fig. 7B, top left plot). Some paths, particularly those with multiple reversals, experienced overshoot followed by an overshoot in the opposite direction, oscillating about the trajectory (Fig. 7B, center middle plot, P5; Fig. 7C, bottom middle plot, P4). On the other hand, some participants opted for a more conservative strategy, never reaching the extremes of the trajectory (Fig. 7B, center left plot, P7).

For each trial, we computed the RMS forearm angle error $\theta_e = \sqrt{1/L \sum_{n=1}^{L} (\theta_t[n] - \theta_{arm}[n])^2}$, where n is a time sample and L is the total number of samples in the trial, and the Pearson correlation coefficient, ρ, between the target trajectory, $\theta_t[n]$ and the participants' response trajectory $\theta_{arm}[n]$. We took the median across repetitions to avoid outlier trials biasing our results. We then averaged across the different path complexity types (i.e., 1-reversal, 2-reversal, and 3-reversal; Fig. 8A, B, left panels) and across different trajectory speeds (i.e., fast, medium, and slow; Fig. 8A, B, right panels). In Friedman tests, we confirmed that the factors "Trajectory Complexity" and "Trajectory Speed" had a significant effect on the RMS trajectory error θ_e (Complexity: $p < 0.001$***, $\chi^2(2, N = 8) = 16$; Speed: $p < 0.001$***, $\chi^2(2, N = 8) = 16$) and significant differences were found between the 1-turn and 3-

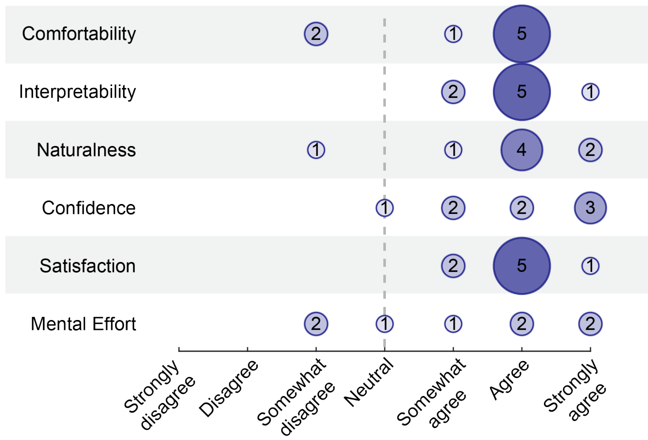

Fig. 9. **Likert survey results.** After the study, participants answered 6 questions on a 7-point Likert survey. Participants generally found the device interpretable and natural, had confidence in the delivered cues, and were satisfied with the device's performance.

turn trajectories ($p < 0.001^{***}$) and between the fast and slow trajectory speeds ($p < 0.001^{***}$) in follow-up Wilcoxon signed-rank tests. The results were similar when using the alternative metric of the Pearson correlation coefficient, ρ. These results indicate that motion guidance cues provided by the NURing are more effective for less complex trajectories (one-reversal and two-reversal) presented at slower speeds (slow and medium speeds), though the relatively low RMS error under all conditions indicates that the trajectories were readily interpretable and comprehensible. Despite variability in individual response profiles, the overall performance patterns indicate that the cues conveyed sufficient guidance information for participants to follow complex trajectories.

D. Survey Results

We inverted the data of the negative valence questions for visual presentation and ease of discussion. Participants, on average, rated the device well above neutral, with a grand mean of 5.6 when the responses were encoded numerically (i.e., Strongly disagree = 1, Neutral = 4, Strongly Agree = 7; Fig. 9). Most notably, participants felt the devices' cues were easily interpretable and natural. Participants were confident in the cues they received and were satisfied with the performance of the device for delivering motion guidance cues. Of particular interest to this work was the rating of "mental effort," with a mean score of 5.1. This suggests that low cognitive effort is required to operate the device. Indeed, some participants found the device exceedingly easy to operate, with one participant in the open-ended survey questions stating that "When my finger was pulled, it felt like my arm was moving on its own." This response, along with others that indicated that the device felt as if someone was tugging or pushing on their finger, highlight the natural response of the hand and arm in the direction of fingertip deflection and were consistent with the intent of the NURing. On the other hand, some participants (2/8) did rate the device comfortability below neutral and others found it challenging to hold their finger out for longer periods of time. Taken together, these survey results indicate that the NURing was highly effective at delivering the desired motion cues, but some additional degree of personalization may be required for the device to be used comfortably and without significant physical or mental effort for all persons.

V. Discussion

As currently presented in this paper, the NURing is capable of precise lateral guidance in the peripersonal space through intuitive and salient fingertip deflection. Motion cues could be effectively generated at frequencies of up to 1 Hz (task 1). This high bandwidth on motion cues allowed participants to rapidly reach the target direction in, on average, 2.79 s and with a median error of 1.45° (i.e., less than 11 mm fingertip deviation) in the single-direction guidance task (task 2). In the trajectory tracking task (task 3), participants were tasked with following an unknown trajectory whose direction changed up to a maximum of three times, yet were still able to achieve tracking errors of 7°, on average. Critically, these results were achieved with minimal exposure to the NURing and its motion guidance cues, and with a simple proportional controller.

Compared to similar user studies exploring wearable fingertip guidance, we found that our device's performance offered improvements in several areas. First, given the salience and intuitiveness of the cues conveyed through finger deflection, users did not need to employ complex search strategies in order to reach the desired target direction, with most users overshooting and undershooting a maximum of one or two times before rapidly settling at the target direction (Fig. 6A). Similarly, during the trajectory tracking tasks, we witnessed very few degenerate strategy attempts (Fig. 7) wherein a user would misinterpret the cue completely and be unable to return to the desired path. The lack of need for a search strategy is also reflected by the rapid task completion times in task 2 (Fig. 6C). Lastly, the results of the single-direction guidance task show that in 96% of trials (excluding the trials from P7; see Sec. IV-B), participants were able to successfully reach the intended direction without intensive training. The development and integration of simple training tasks will hopefully improve results across all metrics, particularly during the transition into three-dimensional guidance.

While vibrotactile devices have demonstrated feasibility in guiding users to nearby objects [4], [5], [6], the NURing advances this concept by leveraging kinesthetic feedback to support accurate and responsive directional guidance. Our results ($<$ 3 s task completion, $<$ 11 mm localization accuracy) in a simple one-dimensional setting suggest a potential for significant improvement over current state-of-the-art vibrotactile devices for three-dimensional guidance and localization ($\approx$ 35 s task completion, $<$ 100 mm localization accuracy [4]). Unlike vibration-based cues, which may be missed or require cognitive interpretation, the physical salience of fingertip deflection enables more intuitive responses, consistent with proprioceptive expectations. We believe this alignment between cue and motor response also makes the signals harder to misinterpret. The

NURing thus presents a compelling alternative for tasks that benefit from high spatial precision and rapid, intuitive feedback.

VI. Limitations and Future Work

As with any closed-loop feedback system, there are significant opportunities for improving the NURing controller to account for the dynamics of the user. To do this, we intend to create a model of a user's behavior based on data collected in the study presented here and develop a strategy wherein the device can be tuned to the user *in situ*, creating a user-specific controller profile.

In addition, we intend to further study the mechanism by which the device is able to generate such strong responses without prior training. These insights will aid us as we move the device into three-dimensional guidance. While not characterized for this paper, during preliminary testing we have found that deflection cues in the flexion and extension direction also generate strong natural responses similar to those presented herein. We believe one of the greater challenges faced will be in generating a salient and natural "move forward" cue that does not conflict with the fingertip deflection cue. In contrast, during preliminary testing we have already discovered that by momentarily pulling on all three tendons together, we are able to generate a strong "stop" cue.

Given the ability of this device to provide guidance to individuals with sensory limitations, we see potential in the NURing serving as an assistive device. In recent exploratory testing we performed with a user that was visually impaired, we found that the NURing was able to guide the user toward a target object in three-dimensional space with little to no training. Even more impressively, that user was also able to use the NURing to navigate around a crowded room while holding a white cane, demonstrating that our device does not interfere with existing navigational tools but rather may be used in conjunction with them. Following this experience, the user told us, "I can't stop thinking about how much using this design made me feel in control," an insight that we feel is invaluable and highlights the importance of allowing a user to maintain a sense of agency when using assistive devices.

We have also begun developing a camera-enabled version of the device to implement real-world guidance and navigation capabilities. By mounting a camera on the drive band, we aim to move away from the tethered experimental platform and leverage existing mapping and tracking technologies to identify objects in the user's peripersonal space and guide the hand toward a desired target. Additionally, we hope to be able to include scene recognition for true independent interaction guidance. An example of this application would be to allow a user with visual impairments to enter an elevator and have the device scan the environment and identify the touch screen. The user would then be able to communicate their desired floor to the device and have the device guide their finger to the appropriate icon.

Several human-centered design improvements are planned for the device. The current device, as presented in this paper, prioritized validating the underlying deflection mechanism as a guidance cue. As such, component selection focused on configurability and robustness, rather than size or efficiency. Future iterations will incorporate more compact and power-efficient actuators, miniaturization of the power and motor amplifiers, and an overall streamlining of the system. We also aim to improve the wearable aspects of the system by improving user comfort, easing the donning and doffing process, and ensuring consistent positioning of the drive elements across uses. To achieve this, we are exploring the use of a semi-rigid wearable with self-aligning features. These refinements will reduce the drive band's bulk and weight, improving ergonomics and enabling unobtrusive use (e.g., under clothing) in daily or assistive settings.

The study presented here, which included eight participants aged 22-46, yielded statistically significant results and demonstrated the feasibility of using fingertip deflection for motion guidance. In future studies, we plan to significantly expand our participant pool, which will allow us to better understand participant differences, such as those that led P7 to perform poorly in task 2, better represent a wider range of ages, body types, and sensorimotor abilities, and assess training and adaptation to the NURing over extended use periods.

VII. Conclusion

In this paper, we introduced the NURing, a novel, lightweight wearable device for generating guidance cues through fingertip deflection. Our device can generate on-demand kinesthetic feedback without obstructing the fingertips or hands, allowing the user to perform dexterous tasks while still wearing the device. We also showed that our cue modality—fingertip deflection—performed well in inducing a movement response from the user with no prior training. Our study showed that by delivering salient and natural cues, the device is able to guide users quickly and accurately toward an intended target position using a classical proportional controller. Ultimately, we believe that this device, with its unique and natural cue modality and on-demand capability, has the potential to unlock new forms of kinesthetic interaction and restore interactions that may have been previously unavailable to people with sensory limitations.

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