DERS: Distribution of Eccentric Rotational Skin-stretch induce Directional Force Sensation on a Wrist

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Abstract. Presenting force-tactile feedback while keeping the hand free and maintaining perceptual transparency is a crucial challenge for achieving natural interaction. In this study, we propose DERS (Distribution of Eccentric Rotational Skin-Stretch), a novel skin-stretch stimulus method using eccentric rotation. DERS employs tactors with rotation axes offset from the center of the contact surface, generating directional shear deformation on the skin through rotational motion. The system presents two-degree-of-freedom force direction and intensity without additional mechanical grounding by coordinating eccentric tactors placed at four locations around the wrist. Two psychophysical experiments were conducted. Perceived intensity followed Stevens' power law with a near-linear exponent. Two-alternative direction classification was high on the palmar, dorsal, and radial sides but lower on the ulnar side, where the ulnar styloid process limits uniform skin contact. In the eight-direction experiment, responses were significantly concentrated toward the target for most directions, with cardinal directions more accurately localized than diagonals and a systematic bias in the downward direction arising from the same ulnar-side constraint.

Keywords: Haptic display · Skin-strech · Wearable.

1 Introduction

Haptic feedback is essential for natural interaction in extended reality (XR) environments, enabling users to perceive virtual object properties and receive guidance cues. However, effective haptic presentation must not compromise the user's ability to manipulate real objects—a property known as perceptual transparency [4]. Devices that occlude the palm or fingertips can cause discomfort during physical interactions and degrade immersion through their mere presence. Consequently, haptic systems that leave the palm free [10] while delivering clear force-directional cues have become a central design goal.

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Wearable haptic devices have been explored at various body locations to address this challenge [6]. Fingertip-mounted devices offer high perceptual acuity but inevitably interfere with grasping [6]. Arm-mounted systems [1] provide force feedback away from the hand, yet their size and degree of freedom limit practical deployment. The wrist has emerged as a promising site: it accommodates device mass without impeding finger dexterity and maintains proximity to the hand for perceptual relevance [7, 5, 12]. Nevertheless, wrist-worn devices face inherent difficulties in conveying directional force sensations. Linkage-based mechanisms achieve precise directional presentation but result in bulky assemblies [5], while vibrotactile and squeeze-based approaches such as Tasbi [7] remain compact at the cost of limited directional resolution.

Skin-stretch stimulation offers an alternative that balances mechanical simplicity with directional cueing capability. Provancher et al. demonstrated that tangential skin deformation at the fingertip effectively conveys shear force direction [8], and subsequent work extended this principle to wearable contexts [6]. For forearm applications, Shim et al. proposed QuadStretch, employing a counter-stretching mechanism with rack-and-pinion transmission to achieve multi-dimensional feedback without a grounding frame [9]; however, the gear-based design adds mechanical complexity. Chinello et al. developed a simpler bracelet-type device with four rotational tactors for navigation guidance [2], demonstrating effective forearm motion cueing. Yet their evaluation focused on navigation tasks rather than force direction perception, leaving open the question of directional accuracy. For wrist-worn applications, Umehara et al. similarly employed four concentric rotational tactors [11, 12], but psychophysical evaluation revealed limited directional discrimination, suggesting that concentric rotation alone provides insufficient directional cues for force perception.

We propose DERS (Distribution of Eccentric Rotational Skin-stretch), a skin-stretch stimulation method that addresses this limitation. The key insight is that offsetting the rotation axis from the tactor center imparts directional bias to skin deformation, producing clearer directional cues than concentric rotation. By assigning four tactors dual roles as both stimulus generators and mechanical grounds, DERS achieves two-degree-of-freedom force presentation without additional mechanisms. The contributions of this paper are:

1. A novel eccentric rotational skin-stretch method that maintains mechanical simplicity while improving directional presentation over existing rotational approaches
2. Psychophysical characterization of directional and intensity perception, revealing anatomical constraints (ulnar styloid process) and systematic biases that inform future device optimization

2 Proposed Method

2.1 Principle of DERS

DERS presents directional force sensation by applying shear deformation to the skin using tactors with eccentric rotation axes. Unlike conventional rotational

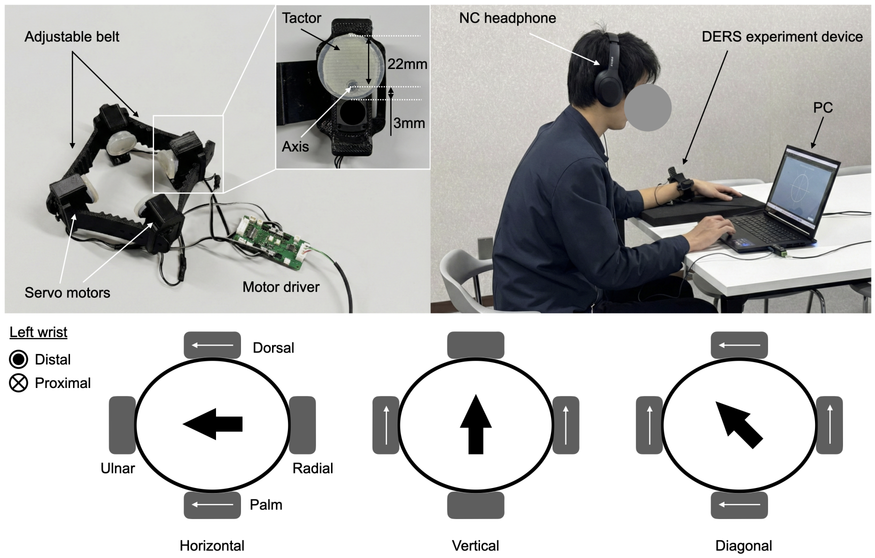

Fig. 1. Overview of the DERS system: (top left) hardware appearance showing the four eccentric tactors, (top right) experimental environment with a participant wearing the device, and (bottom) control law illustrating coordinated tactor activation for directional stimulus presentation.

shear stimulation where the axis is centered, DERS offsets the rotation axis from the contact surface center, imparting directionality to the skin deformation. When the tactor rotates, points near the axis displace minimally while those farther away displace more, creating a perceived unidirectional shear force.

Based on this principle, DERS arranges four tactors around the wrist (palmar, dorsal, radial, ulnar), each independently angle-controlled. By placing two tactors in opposing positions and driving them synchronously, a synthesized force perception along that axis is generated. Combining the four tactors enables stimulus presentation in any direction on a two-dimensional plane.

2.2 Hardware Implementation

The apparatus consists of four robot servo motors (Orbray) with 0.1° resolution, each fitted with an eccentric tactor (offset: 22 mm). Tactors on the radial and ulnar sides feature a curved contact surface (ϕ30 mm) conforming to wrist curvature. A 3 mm self-adhesive silicone gel layer ensures stable skin contact and efficient shear transmission.

The motor housing is equipped with a hook-type belt loop, allowing the device to be worn on the wrist with adjustable tactor positioning. During experiments, the device was fastened to maintain stable tactor–skin contact without causing discomfort (Figure 1).

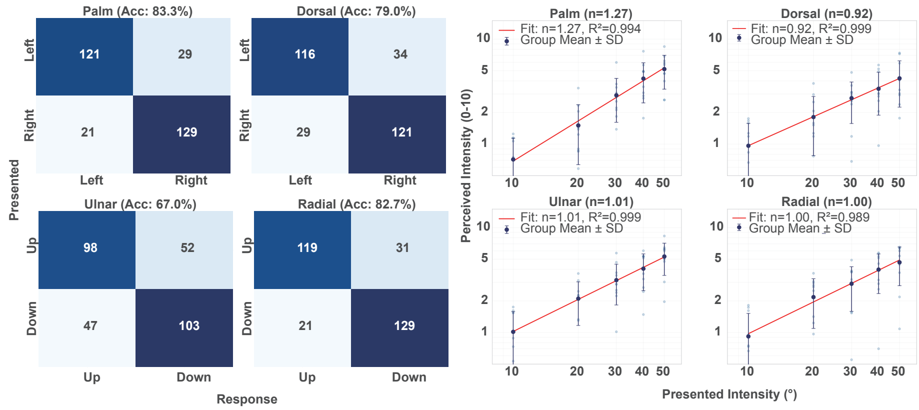

Fig. 2. Results of Preliminary Study: (left) confusion matrix showing direction classification accuracy for each tactor, and (right) relationship between stimulus intensity (rotation angle) and perceived intensity, demonstrating Stevens' power law characteristics.

2.3 Control Law

Horizontal stimuli (left/right) are generated by synchronously driving the palmar–dorsal tactor pair; vertical stimuli (up/down) by the radial–ulnar pair. Diagonal directions combine both axes. Stimulus intensity is controlled by rotation angle (10°–50°), with larger angles producing greater shear deformation and perceived intensity (Figure 1).

3 Experiments

Two experiments were conducted to verify that DERS can present stimulus intensity and direction.

Ten healthy adults (7 males, 3 females; aged 19–31, mean 23.6 years) participated in the experiment. All participants were right-handed and had no impairments of the wrist or hand. The experimental procedure was conducted in accordance with a protocol approved by the ethics committee.

3.1 Preliminary Experiment: Evaluation of Stimulus Characteristics with Single Tactors

This experiment aimed to verify that each tactor can independently present stimulus intensity and direction. Specifically, we sought to confirm the increase in perceived intensity with rotation angle, the discriminability of rotation direction, and the consistency of perceptual characteristics across tactors.

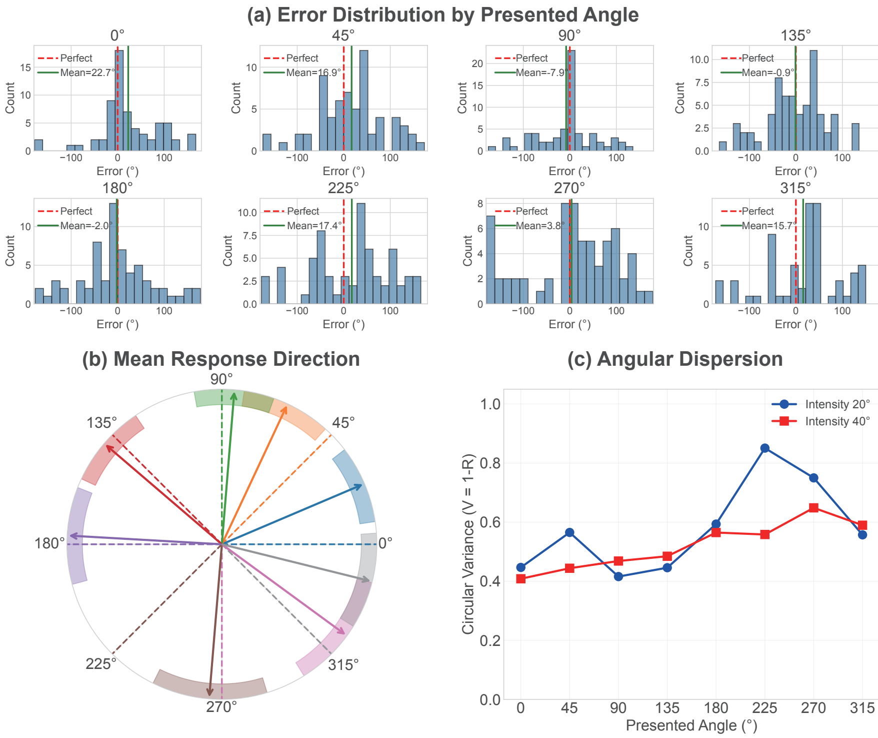

Fig. 3. Results of the eight-direction presentation experiment. (a) Signed angular error distribution per presented direction; the green line marks the *linear* arithmetic mean of signed errors. At 270°, where the response distribution is broad and partially bimodal, positive and negative wrap-around errors cancel so that the linear mean lies near zero; the *circular* mean shown in (b) is the appropriate descriptor in this case (see text). (b) Circular mean response direction (solid arrows) vs. presented direction (dashed); shading indicates the 95 % confidence interval. (c) Angular dispersion $V = 1 - R$ at two intensity levels (rotation angles of 20° and 40°).

Stimuli The following stimuli were presented in this experiment. Rotation angle was set at five levels: 10°, 20°, 30°, 40°, and 50°. Rotation direction consisted of two levels: forward and reverse. Stimuli were presented at four tactor locations: Palmar, Ulnar, Dorsal, and Radial. Each trial consisted of a single rotation pulse with a short rise–hold–release angular-velocity profile of approximately 1 s total duration, identical across all tactors and intensity levels. Each condition was repeated three times, resulting in a total of 120 trials per participant.

Procedure This experiment was conducted using magnitude estimation and two-alternative forced choice methods, with participants responding to both direction and intensity for each trial. Participants were seated in a chair, wore the device, and received instructions about the purpose and procedure of the experiment. First, a practice session of five trials was conducted, ensuring that the 50° stimulus was included. Subsequently, while listening to white noise through headphones, participants responded to the presented stimuli regarding direction and intensity. For direction, participants identified horizontal (left/right) or vertical (up/down). For intensity, participants responded with a numerical value based on a reference where the maximum stimulus during the practice session was defined as 10.

Results Regarding direction classification accuracy, the Palm, Dorsal, and Radial tactors demonstrated high accuracy rates averaging 81.7%, whereas the Ulnar tactor showed significantly lower accuracy at 67.0% ($\chi^2 = 41.16$, $p < 0.001$; Figure 2, left). Additionally, accuracy tended to improve with increasing stimulus intensity, rising from 72.7% at 10° to 87.0% at 50°.

For perceived intensity, the relationship between rotation angle and perceived intensity followed Stevens' power law ($\psi = kS^n$) for all tactors ($R^2 > 0.99$; Figure 2, right). The mean power exponent was $n = 1.062$, indicating an approximately linear relationship between physical stimulus intensity and perceived intensity.

3.2 Main Experiment: Eight-Direction Presentation

This experiment aimed to verify that coordinated control of multiple tactors enables stimulus presentation in eight directions, including diagonal directions. We evaluated the accuracy of directional perception and the presence of systematic biases.

Stimuli Eight directions were tested at 45° intervals starting from 0°. Intensity was set at two physical rotation-angle levels, 20° (low) and 40° (high). Each condition was repeated three times, and a total of 48 trials were presented in random order. The temporal profile of the stimuli was the same as in the preliminary experiment.

Procedure In the same environment as the preliminary experiment, participants responded by plotting a point on a circle. The angle of the response position recorded the perceived direction, while the distance from the center simultaneously recorded the perceived intensity.

Results The overall mean absolute error for directional perception was 59.2° (Figure 3a). Cardinal directions (up, down, left, right) showed significantly lower error than diagonal directions ($p = 0.014$). The Rayleigh test confirmed that responses were non-uniform (i.e., showed significant angular concentration) for all presented directions ($p < 0.05$).

Regarding systematic bias, the circular mean of response direction at 270° (downward) was 323.8°, corresponding to a +53.8° bias toward the radial–volar quadrant (Figure 3b). The linear mean shown in Fig. 3a (+3.8°) appears close to zero because the 270° signed-error distribution is broad and partially bimodal, so positive and negative wrap-around errors cancel out; the circular mean is the appropriate descriptor. The V-test confirmed concentration toward the presented direction for all directions except 270° ($p < 0.001$).

Concerning the effect of intensity, the high-intensity condition (40°) showed a tendency toward improved accuracy, although this did not reach statistical significance. In particular, response concentration improved for directions that were difficult to perceive (Figure 3c).

4 Discussion

4.1 Preliminary Experiment: Tactor Characteristics

Regarding intensity perception, all tactors conformed to Stevens' power law (mean power exponent $n = 1.062$) with high goodness of fit. The power exponent being close to 1 indicates an approximately linear relationship between the presented physical stimulus intensity and perceived intensity, which is consistent with trends reported in previous studies [3, 11]. This demonstrates that the device operated as expected and successfully presented stimuli.

The preliminary experiment revealed differences in direction presentation accuracy depending on tactor placement. In particular, the accuracy of the Ulnar tactor at 67.0% was significantly lower compared to the others. This is likely because the ulnar styloid process, a bony prominence, protrudes at the wrist surface where the skin and subcutaneous tissue are thin. When the tactor was pressed against this area, the contact surface of the eccentrically rotating tactor likely did not adhere uniformly to the skin, resulting in uneven contact pressure or the bony contour inhibiting the generation of shear deformation.

Interestingly, while direction classification accuracy varied among tactors (particularly low on the ulnar side), intensity perception characteristics were consistent across all four tactors. Intensity perception largely depends on the total contact area and cumulative pressure, allowing intensity to be perceived as long as the total amount of deformation is transmitted even if the tactor is somewhat unstable. In contrast, direction discrimination requires accurate extraction of the vector components of skin deformation and is therefore more sensitive to contact conditions.

4.2 Eight-Direction Presentation Experiment

DERS afforded *coarse* omnidirectional cueing: responses were significantly concentrated toward the target for seven of the eight directions. However, because the overall mean absolute error of 59.2° exceeds the 45° spacing between adjacent targets, we interpret the current system as a continuous 2-DoF directional cue rather than a reliable discrete eight-way display. Cardinal directions showed lower error than diagonals, consistent with diagonal cues requiring simultaneous activation of two axes.

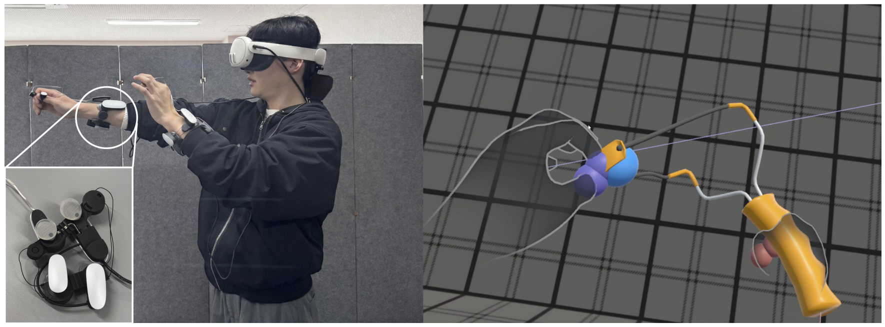

Fig. 4. Prototype application integration: (left) DERS integrated into the FeelFuse commercial haptic device worn by a user experiencing XR content, and (right) in-headset view of the virtual environment.

The most prominent bias was observed at 270° (circular-mean displacement +53.8°). This direction is driven by the Ulnar–Radial pair, and since the ulnar side already shows lower efficacy (67.0%), a weaker ulnar shear pulls the synthesized vector toward the radial side. The 270° response distribution is moreover broad and partially bimodal (Fig. 3a), suggesting that some participants could not robustly recover a downward direction—i.e., downward is the limiting direction of the current configuration rather than simply a shifted one. Response concentration (R) improved at higher intensity for 225° and 270° (Fig. 3c), indicating that a direction-dependent gain could partially compensate for this bias without hardware changes.

4.3 Comparison with Prior Rotational Skin-Stretch Devices

A direct comparison between eccentric and concentric rotational tactors was outside the scope of this study, which we acknowledge as a limitation. Umehara et al. [11, 12] evaluated four *concentric* tactors at the wrist with a methodologically similar protocol, reporting clearly perceivable intensity but limited directional discrimination; the 81.7% two-alternative accuracy reported here on the anatomically favorable sides thus represents a plausible, though not formally established, improvement attributable to the eccentric axis. Two caveats should be noted: because the armband is compliant, the effective rotation point is not strictly fixed to the skin and the resulting shear field is a *biased* rotational field rather than a pure translation; and the ulnar-side degradation is anatomy-driven and would likely affect any rotational skin-stretch device at the same location. A within-subjects, same-protocol comparison with concentric tactors remains an important direction for future work.

4.4 Prototype Application Integration

We integrated the DERS method into the FeelFuse commercial haptic device[1] and built a prototype that maps reaction forces, tension, and virtual gravity in an XR scene to DERS stimuli (Fig. 4). An important direction for future work is to investigate how visual information in XR interacts with the directional biases characterized above—in particular, whether visual cues perceptually compensate for the 270° downward bias, or whether the haptic and visual channels yield distinct spatial interpretations that must be jointly designed for.

5 Conclusion

We proposed DERS, a mechanically simple skin-stretch method using eccentric rotational tactors to present directional and intensity cues at the wrist without additional mechanical grounding. Perceived intensity followed Stevens' power law with a near-linear exponent (mean $n = 1.062$, $R^2 > 0.99$), and two-alternative direction classification reached 81.7% on the palmar, dorsal, and radial sides and 67.0% on the ulnar side, where the ulnar styloid process limits uniform skin contact. The eight-direction experiment showed significant angular concentration toward the target for seven of eight directions (overall mean absolute error 59.2°), with direction-dependent accuracy that includes a systematic +53.8° downward bias traceable to the same ulnar-side constraint. These results characterize DERS as a wearable, palm-free directional haptic primitive with well-understood anatomical and perceptual properties. Priorities for future work include a direct comparison with concentric tactors, anatomy-aware gain control for the ulnar side, and investigation of how visual information in XR interacts with the characterized directional biases.

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