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# Continuous Skin-Stretch Feedback for Rendering 3D Vector Information

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**ABSTRACT** Most of the previous haptic interfaces provides tactile feedback directly to the hand, which can impede the operability. Noting the issue, we propose a haptic system that can provide 3D vector information with continuous skin-stretch feedback. We designed the system to render a 3D vector by combining two orthogonally located continuous skin-stretch modules whose orientation could be controlled. To optimize the stimuli, we conducted a psychophysical experiment that measured human sensitivity to the orientation of the continuous skin-stretch feedback. Considering the asymmetry of tactile sensitivity, we collected the data at two locations of the forearm. The results indicate that the participants were more sensitive to the angle change when the skin-stretch feedback was aligned in the proximal-distal direction. Based on the information, we built an algorithm to set the rotation angle of the skin-stretch module to render any target 3D vector. We conducted two experiments for virtual interaction to evaluate our proposed method. In Experiment 1, we tested if adjusting the skin-stretch orientation could improve the human perception of the virtual surface features, and the result indicated a significant improvement in the surface feature perception with the orientation adjustment. Experiment 2 tested a participant's ability to follow a random 3D contour under two conditions, visual cue (V) condition, and visual and continuous skin-stretch (V+CF) cues condition. For the V+CF condition, the skin-stretch interface rendered the error 3D vector to the participant's forearm. The result indicated a significantly lower root-mean-square error for the V+CF condition than the V condition. Thus, the addition of the continuous skin-stretch feedback benefitted the participants to stay closer to the target virtual contour than with visual information only.

**INDEX TERMS** Haptic feedback, skin-stretch feedback, trajectory following, contour following.

## I. INTRODUCTION

Since its birth in the early '90s, the field of haptics has advanced to give tactile information to a user for intuitive and precise interaction with virtual and remote environments. Notably, the haptic technologies are receiving new anticipation as the virtual reality, and robotics industries prosper in the recent decade. The most typical haptic system is in the form of a force feedback interface, which provides kinesthetic sensation to a user via a tool that a user is holding during the interaction [1], [2]. A more recent type of haptic system is the cutaneous feedback interface, which imparts the tactile sensation directly to the user's skin. One of the earliest cutaneous feedback interfaces is the contact location display (CLD) proposed by Provancher in the early 2000s, which provides the contact location information with a virtual object at the fingertip [3], [4]. Since then, various cutaneous or cutaneous-plus-force feedback hybrid haptic interfaces have been suggested by increasing the degrees of freedom in tactile information [5]–[8]. Most of the haptic interfaces proposed so far are focused on providing as realistic tactile sensation as possible, to the hand. Thus, such a haptic interface is supposed to have limited usability of hand while the user is wearing or using the interface. We addressed the problem by providing the skin-stretch feedback to a user's forearm.

The skin-stretch feedback has been a relatively less studied tactile feedback method until recently. The SA-II type mechanoreceptor is known to be mainly responsible for perceiving the lateral stretch of the skin [9]. It has the

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characteristics of low density and indentation thresholds, compared to FA-I and SA-I type mechanoreceptors on the hand [10]. Due to its nature of the less sensitive spatial resolution, relatively fewer haptic devices utilized the skin-stretch feedback to provide the tactile information to the hand [11]–[14]. Recently, we applied the skin-stretch feedback to the dorsum of a hand during the virtual object grasping task and demonstrated that the skin-stretch feedback could modulate the perceived size of an object [15]. In the meanwhile, Bark *et al.* proposed a skin-stretch interface that could stimulate a user's skin on the forearm by rotating a disk [16]. They demonstrated that human subjects could successfully perceive and identify the rotation of the disk rendered as the skin-stretch stimuli. O'Malley's group suggested a skin-stretch interface with rocker geometries, worn on the upper/lower arm. They demonstrated the effectiveness of the feedback in virtual object perception [17], [18]. Also, Chinello *et al.* proposed a skin-stretch interface that could provide a user with a 2 DOF direction cue for haptic guidance More recent studies proposed similar 2 DOF skin-stretch interfaces for teleoperation and prostheses control [20], [21]. Overall, fewer researchers have developed the skin-stretch interface compared to other types of haptic feedback, and most of them were to provide haptic information to a hand. Other types of skin-stretch feedback interfaces were designed on the upper or lower arm. They could provide 1 or 2 DOF directional information to a user, which is limited in rendering 3D vector information. Another notable limitation of the previous methods is that the contact element is stationary once it stretches the skin, limiting the range of representing the haptic cue.

The contour or trajectory following is a task asking a user to move along a designated path in a 2D or 3D space. In terms of haptic feedback, the trajectory following has been often employed to measure the effect of haptic feedback on a motor task. Kuchenbecker *et al.* showed that the contact location information at the fingertip could improve the accuracy of the contour following task, compared to the force feedback alone [22]. Park *et al.* demonstrated that the addition of cutaneous feedback to force feedback improved the perception of the surface feature during a contour following task [23]. Also, multiple references in rehabilitation show that haptic feedback can supplement the trajectory following tasks for motor learning [24]–[26]. However, when it comes to the effect of skin-stretch feedback, it is harder to find a reference that investigated the effect of haptic feedback on the task of following a complex 3D contour.

In the present study, we propose a skin-stretch haptic system that can effectively render 3D vector information. A typical haptic interface is designed to be held or worn on a hand, which can impede a user from using other types of interfaces. Noting the issue, we had views upon the skin-stretch feedback on the forearm. For the sake of the useability of the feedback method in transmitting complex information, we designed a haptic system that can represent a 3D vector with skin-stretch feedback at multi locations on the forearm. We focused on two issues in rendering a 3D vector with the skin-stretch cues. First, we prevented a user from getting insensitive to the skin-stretch stimuli when it is stationary. We addressed the issue by proposing a *continuous skin-stretch haptic interface*. Next, we noted that when rendering geometry information with the 3D vector, a user's ability to sense the surface feature would be reduced if the change of stimuli is below the perception threshold, or just noticeable difference (JND). We avoided the problem with a *skin-stretch orientation adjusting method* where the amount of skin-stretch orientation is controlled based on the human perception of the skin-sliding orientation. We first measured the perception threshold of the skin-stretch orientation with a standard one-interval two-alternative-forced-choice (1I-2AFC) experimental paradigm in a preliminary experiment. Based on the JND by orientation, the skin-stretch orientation is calculated from the target vector. Then, the skin-stretch orientation changes when the delta of the orientation is over the JND. The algorithm mitigates the low spatial resolution issue of the skin-stretch feedback by increasing the perceptual contrast of tactile cues. We tested the feasibility of our proposed system in two experiments, i) a surface feature identification experiment, and ii) a contour-following task where the proposed haptic system provided a user with the error information from the target by rendering a 3D vector. Before the main experiments, we measured human sensitivity to continuous skin-stretch stimuli by the position and orientation, for optimized tactile feedback.

The objectives of the present study are, i) proposing a skin-stretch haptic system to render 3D vector information effectively, and ii) demonstrating the validity of the skin-stretch system for virtual interaction. Typical kinesthetic feedback can let a user feel the vivid sensation of touching a virtual object. However, the user cannot use other functionality of the hand while s/he is using the haptic interface. On the contrary, the user can still hold or manipulate an interface at hand when the skin-stretch feedback is provided to the forearm. In this context, the present study proposes the skin-stretch haptic system and its validity in rendering 3D vector information during virtual interaction.

The rest of this paper is organized as follows. First, we describe the skin-stretch feedback interface and haptic rendering algorithm for a 3D vector. In the next section, we present the results of the preliminary experiment, which measured human tactile sensitivity to continuous skin-stretch feedback by the orientation and the location on the forearm. Then, the haptic rendering algorithm is optimized to enhance a user's perception of virtual surface features based on the human perception experiment data. Next, we evaluated our proposed haptic system in providing geometry information of a virtual object with two experiments. Finally, we discuss the implications of the experimental results and conclude the study by mentioning future work.

## II. METHODS

### A. A CONTINUOUS SKIN-STRETCH HAPTIC INTERFACE TO RENDER 3D VECTORS

#### 1) DESIGN REQUIREMENTS

The goal of the present study is to build a haptic system that can effectively provide a 3D vector cue while a user can freely use his/her hands. In the previous studies, the skin-stretch was implemented by laterally moving a contact element on a user's skin. For such a haptic interface, the maximum displacement or the workspace of the contact element limits the range of skin-stretch feedback. Then, if the magnitude of the skin-stretch does not significantly change over time, a user will become insensitive to the change of stimuli. An effective haptic system should be able to continuously impart the tactile information with skin-stretch without being affected by the mechanical workspace of the contact element. Requirements mentioned above pose multiple constraints on the design of the haptic interface, including i) the wearability on a body part without restricting hand motion, ii) the continuity of the rendered haptic stimulus without being affected by the contact element's workspace, and iii) the ability to represent the 3D vector information via tactile feedback. For i), we decided to place the haptic interface on the user's forearm considering human sensitivity to tactile stimuli by body parts. Previous studies show that human tactile sensitivity improves in a proximal to distal direction from shoulder to the fingertip [27], [28]. Thus, we selected the forearm as the location of placing the haptic interface, which is farthest from the shoulder, excluding the hand. Regarding ii), we selected the skin-stretch feedback to provide tactile information to a user since humans are known to be more sensitive to tangential feedback than normal feedback in a glabrous skin area, including the forearm [29]. Besides, we address the issue of limited workspace with skin-stretch feedback by designing a continuously skin-sliding mechanism. Finally, for iii), we decided to use two continuous skin-stretch haptic feedback modules, each of which can render a 2-D vector on the skin. Thus, by combining the two 2D vectors aligned in the orthogonal directions can create a 3D vector.

#### 2) A CONTINUOUS SKIN-STRETCH HAPTIC INTERFACE

Figure 1 shows a prototype of a skin-stretch haptic interface worn around a forearm. The interface consists of two skin-stretch modules, each of which can create the sensation of a 2D vector by continuously sliding a contact element. The module was fabricated with a 3D printer (ProJet 3500, 3D Systems, USA) and weighes 176.7 g. The dimension of the module is 152.24 × 84.6 mm × 68.25 mm, which was decided by considering that it would be comfortably worn around an adult's forearm.

A skin-stretch module consists of three parts, the base, the skin-sliding part, and the lid part, as shown in Fig. 2. At the endings of the base are located buckle structures to install belts to fix the module to the forearm. The skin-stretch part has a caterpillar mechanism that can provide continuous skin-stretch feedback by the rotation of a DC motor (HS-35D, Hitec, Korea). We attached silicon bumps on the chain to reduce the friction with the skin so that it can slide by minimizing discomfort. The lid part includes a servo motor (DES281BBMG, Graupner, Germany), which controls the orientation of the skin-stretch.

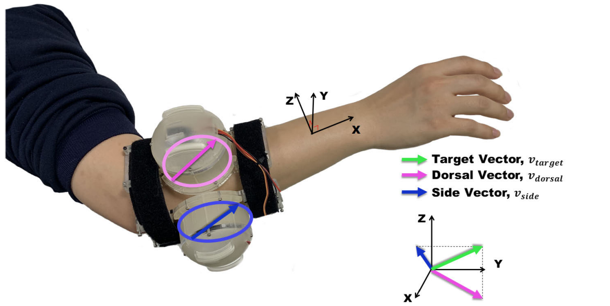


**FIGURE 1.** A prototype of a skin-stretch interface to continuously render a 3D vector worn around the forearm.

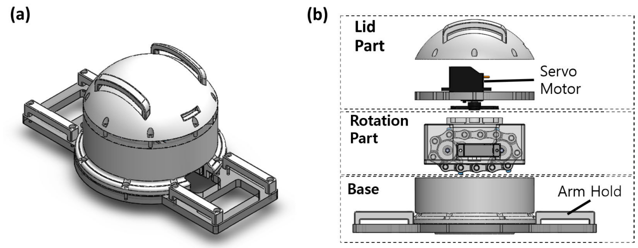


**FIGURE 2.** (a) A CAD design of a skin-stretch module. (b) The assembly of the skin-stretch module.

Figure 3 illustrates the mechanism of creating and controlling a skin-stretch stimulus. Figure 3 illustrates the mechanism of creating and controlling a skin-stretch stimulus. As shown in Fig. 3(a), the rotation of a caterpillar laterally stretches a user's skin (red arrow), and the intensity of the stimulus can be controlled by adjusting the torque of the motor attached to the drive sprocket. Figure 3(b) shows the top view of the skin-stretch module. The orientation of the skin-stretch (green arrow) is controlled by rotating the entire skin-stretch part along the z-axis.

### B. RENDERING A TACTILE CUE IN 3D VECTOR WITH THE CONTINUOUS SKIN-STRETCH HAPTIC INTERFACE

The proposed skin-stretch interface can render a 3D vector by combining two 2D vectors on orthogonal planes, one on the dorsal surface and the other on the side of an arm. Given a target vector $\mathbf{v}_{target} \in \mathbb{R}^3$, two vectors corresponding to the two skin-stretch modules can be calculated as,

$$\mathbf{v}_{dorsal} = \boldsymbol{P}_{dorsal}\mathbf{v}_{target} \text{ and } \mathbf{v}_{side} = \boldsymbol{P}_{side}\mathbf{v}_{target}, \quad (1)$$

where $\boldsymbol{P}_{dorsal}$ and $\boldsymbol{P}_{side}$ are projection matrices for the dorsal and side skin-stretch modules, respectively. Then, the orientation of the skin-stretch $\theta_{rot,idx}$ and the sliding velocity $v_{slide,idx}$

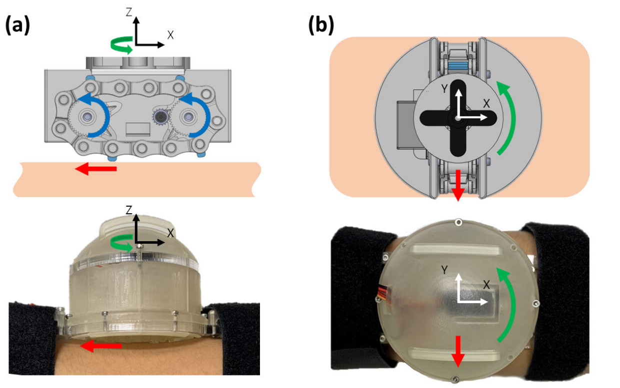


**FIGURE 3.** The illustration of the skin-sliding mechanism. a) The skin slides by the rotation of a caterpillar mechanism. b) The orientation of the skin-stretch can be controlled with a servo motor at the lid part.

(idx ∈ {*dorsal*, *side*}) are

$$\theta_{rot,idx} = \arctan\left(\frac{v_{idx,y}}{v_{idx,x}}\right), \quad (2)$$

$$v_{slide,idx} = \alpha_{slide}\,|\mathbf{v}_{idx}|, \quad (3)$$

where $v_{idx,x}$, $v_{idx,y}$, and $\alpha_{slide}$ are the magnitude of $\mathbf{v}_{idx}$ in x and y axes, and a sliding constant, respectively. Thus, a combination of two skin-stretch stimuli can represent a 3D vector. The sliding constant $\alpha$ was calculated from the maximum rendering distance 2 cm and the maximum sliding velocity of 3.6 cm/sec. We used an Arduino Uno (Arduino, Italy), to control the motors of the skin-stretch interfaces simultaneously. The motors can move synchronously since the command is sent in the same packet and processed in the same loop. An experimental computer sent the command for the velocity and orientation with Serial communication. It should be noted that the skin-stretch keeps moving the caterpillar to provide the 3D vector information unless the $|v| = 0$ (v: target vector). In contrast, a typical skin-stretch interface would have moved the contact element by the desired displacement and stood stationary. In this sense, we call our proposed method as *continuous skin-stretch feedback*.

## III. EXPERIMENTS

The previous section explained a skin-stretch feedback interface and a haptic rendering algorithm to impart 3D vector information to a user. We can evaluate the performance of the proposed system for a virtual object rendering, where the delivery of geometry information is crucial. In this regard, optimizing the proposed algorithm with human perception of the tactile cue is necessary. For example, if the change of the haptic stimulus is below the difference perception threshold (or the just noticeable difference), a user would not acquire the desired geometry information of the virtual object. Considering the issue, we first measure the difference threshold of the skin-stretch orientation and optimize our proposed algorithm based on the perception data. Then, we evaluate our proposed haptic system in two experiments for virtual geometry interaction, a surface feature detection and contour following experiments. We developed all experiment programs in Visual C++.

The experimental protocol was previously approved by the Institutional Review Board at KIST and carried out in accordance with the Declaration of Helsinki for research involving human subjects. Informed consent was obtained from all participants involved in the experiments. We recruited the participants from student researchers at KIST and paid each of them \$10 per hour. The participants had no known problem in motoric, vision, or skin problems. We made sure that none of them had any medication before the experiment. We also checked if the experimental environment, including the white noise, vibration, and mechanical stress, did not cause any mental (e.g., reduced attention) or physical illness (e.g., skin irritation). Finally, the participant's skin was tested before the experiment. We checked if the participant's skin was not too sweaty, trying to avoid the tactile element's possible slip.

### A. PRELIMINARY EXPERIMENT: ORIENTATION DISCRIMINATION OF CONTINUOUS SKIN-STRETCH STIMULI

The preliminary experiment evaluated the human ability to discriminate skin-stretch orientation. We measured the JND for the orientation of the skin-stretch, to quantitatively optimize the skin-stretch stimuli to feel uniformly perceptible regardless of the interface location.

#### 1) EXPERIMENT DESIGN

We used a standard one-interval two-alternative-forced-choice experimental paradigm for the experiment design to calculate the JND of the skin-stretch-orientation [30]. The method is based on the signal detection theory (SDT), which assumes the Gaussian distribution of human perception and, thus, the symmetry of the cumulative probability distribution. More details can be found in [31], [32]. During the experiment, a participant is randomly given one of two stimuli, the reference ($\alpha_0$) and the comparison ($\alpha_0 + \Delta\alpha$) and asked to choose a stimulus between the two that feels to match to the one presented for the trial. After a certain number of trials, an experiment session is terminated. Then, the sensitive index $d'$ is calculated from the z-scores of hit rate ($H$) and false alarm rate ($F$) as follows:

$$d' = z(H) - z(F). \quad (4)$$

Let us assume the linearity between the $d'$ and the stimulus intensity. The JND is conventionally defined as the magnitude of stimuli at $d' = 1$, or the inverse of the slope [32]. From the same assumption, given $d'$ values measured for multiple stimulus intensities, the JND value $(\Delta\alpha)_0$ is calculated as

$$(\Delta\alpha)_0 = \frac{1}{\bar{\delta}}, \quad (5)$$

where $\bar{\delta}$ is the average of the relation between $d'$ and the stimulus intensity.

#### 2) PARTICIPANTS

Twelve participants (21∼33 years old, average 26.1±3.2 years old) took part in the experiment, including two females. All of them were right handed and gave signed consent. None of them had any problem with their sense of touch.

#### 3) STIMULI

The rotation of the chain created continuous skin-stretch stimuli. The reference stimuli were defined by the orientation of the skin-stretch, with the lateral direction as the reference orientation, 0 and 90 degrees. The comparison stimuli were decided by the magnitude of $\Delta\alpha$'s as 20, 40, and 60 degrees. We adjusted experimental variables and setting from a pilot test. The chain velocity varied from 0 to 3.6 cm/sec, depending on the magnitude of the target vector. We set the maximum velocity to be 3.6 cm/sec, over which the participants of a pilot test began to feel the pain. Also, we made sure that the skin-stretch feedback did not create skin irritation of the participant during the experiment.

#### 4) PROCEDURE

The experiment measured the JND's of the rotation angle at two locations, where the skin-stretch modules were attached, the dorsal and side surface of the forearm. At each location, the JND's were measured for the two reference orientations, as described in the previous subsection. There were a total of six reference stimuli ($2\alpha \times 3\Delta\alpha$) at each location, and thus six experimental runs by the reference stimuli.

At the beginning of the experiment, a participant was seated in front of a computer. S/he was asked to wear the skin-stretch haptic interface on his/her forearm. Initially, the haptic interface was installed 5 cm away from the front of the elbow toward the wrist. Finding an optimal device installation location can be a significant factor for the sensitivity to the stimuli since the arm dimension, and skin condition varies by each participant. Thus, the interface's position was adjusted to the location where the participant can sense the skin-stretch feedback best. Then, the participant was asked to put his/her lower arm on an X-Ar gravity exoskeletal arm support (Equipos, Manchester, NH, USA), which reduced the arm weight minimizing possible fatigue. Before the main experiment, a participant had a 15-min training session to figure out which are the reference stimulus($\alpha$) and comparison stimuli ($\Delta\alpha$). Each experimental run consisted of 20 trials. On each trial, either a reference or comparison skin-stretch stimulus was randomly selected and presented to the participant. Then, s/he indicated whether the stimulus felt like a reference or a comparison stimulus with a keyboard. The participant's answer for each trial was recorded along with other parameters, including the trial time.

During the experiment, the participant wore a pair of earplugs and headphones with a 31-dB noise reduction. White noise was played on the headphones to block any audio cues from the experimental apparatus. After each block of trials, the participant was instructed to take a 5-min break before continuing the experiment. It took about two hours for each participant to complete the experiment.

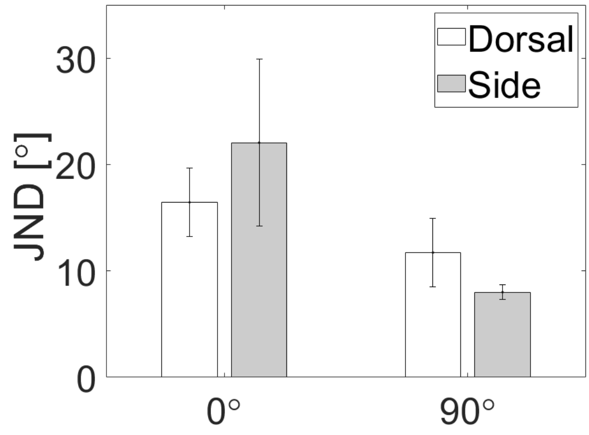


**FIGURE 4.** Mean just noticeable difference(JND) on 0 and 90 degree in two position of forearm. Error bars indicate standard errors.

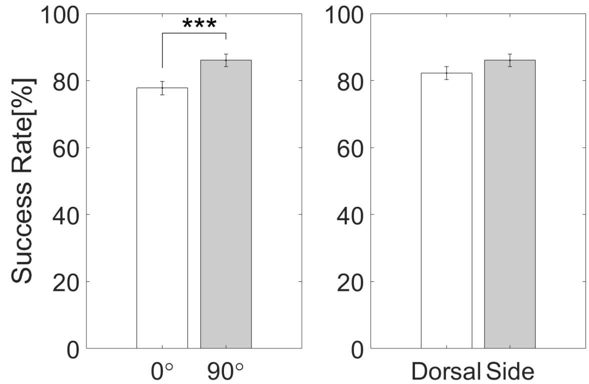


**FIGURE 5.** Mean success rate by reference angle (left) and position (right). Error bars indicate standard errors.

#### 5) RESULTS

Figure 4 shows the mean JND values by the reference angle and the stimulus location. The result of two-way repeated measure ANOVA indicates a significant effect of the reference angle ($F(1,11) = 4.91$, $p = 0.049$, $\eta^2 = 0.31$) and insignificant effect of the location ($F(1,11) = 0.036$, $p = 0.85$, $\eta^2 = 0.003$). The interaction between the two factors was insignificant ($F(1,11) = 1.39$, $p = 0.26$, $\eta^2 = 0.11$). In Fig. 5, the mean success rate is plotted against the reference angle and by the stimulus location. When we conducted a two-way repeated measure ANOVA on the success rate, the effect of reference angle was significant ($F(1,11) = 23.39$, $p = 0.001$, $\eta^2 = 0.68$), while the stimulus location did not ($F(1,11) = 0.075$, $p = 0.79$, $\eta^2 = 0.007$).

Considering the non-uniformity of the skin-stretch sensitivity by the orientation, we estimated the JND for a given angle $\theta$ with the following linear model:

$$f_{JND}(\theta) = \frac{(JND_{90} - JND_0)}{90}\theta + JND_0. \quad (6)$$

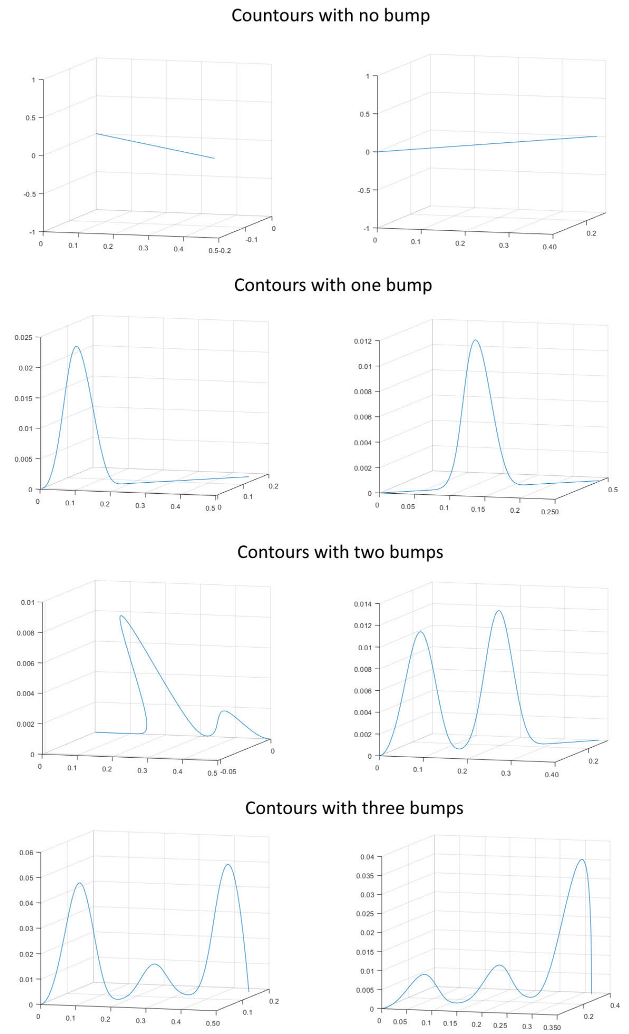


**FIGURE 6. The virtual contour set with surface bumps for Experiment 1. The number of bumps varies between 0 and 3.**

**Algorithm 1** Skin Stretch Orientation Policy Using $f_{JND}$

Set $\theta_{rot,dorsal}$ and $\theta_{rot,side}$
**for** each step **do**
  **for** each $idx \in \{dorsal, side\}$ **do**
    Update $\theta_{rot,idx}$
    **if** $|\theta_{pre,idx} - \theta_{rot,idx}| >= f_{JND}(\theta_{pre,idx})$ **then**
      $\theta_{pre,idx} \leftarrow \theta_{rot,idx}$
      Set the target orientation to $\theta_{rot,idx}$
    **else**
      Set the target orientation to $\theta_{pre,idx}$

Using the model, we modified the target skin-stretch orientation in 2 to increase the perceptibility of the tactile stimulus.

Overall, the results of the preliminary study provide us with quantitative information by the skin-stretch orientation. Based on the results, we optimized the skin-stretch haptic rendering algorithm for the 3D vector to increase the perceptibility of the orientation change and reflecting the difference of orientation change by the stimulus location. The effectiveness of the algorithm is evaluated with two experiments in the next section.

### *B. EXPERIMENT 1: EFFECT OF THE SKIN-STRETCH ORIENTATION ADJUSTMENT ALGORITHM ON SURFACE FEATURE PERCEPTION OF A VIRTUAL CONTOUR*

The previous subsection optimized the skin-stretch algorithm by cutting off the orientation change below the JND. An analogy for this approach can be increasing the contrast of an image. In this subsection, we evaluate the effect of our approach by comparing the participants' ability to perceive virtual 3D surface features under two conditions, with or without the orientation adjustment.

#### 1) EXPERIMENT DESIGN

We designed the experiment to show the effect of adjusting the skin-stretch orientation on the perception of the 3D surface feature. In this regard, the experimental task was to count surface features (bumps) embedded on a random 3D virtual contour. We evaluated the effect of the orientation adjusting method by comparing the result of the participants' performance in the bump counting with or without the adjustment.

We adopted the paradigm of the absolute identification to evaluate the participants' ability to identify the number of bumps on the virtual contours [33]. For the experiment, a set of stimuli with the size of $K$ is constructed first. On each experimental trial, they are randomly presented to the participant. Then, the participant is asked to identify what stimulus is presented to him/her among the $K$ stimuli set. After $n$ trials, the estimate of information transfer ($IT_{est}$) can be calculated from a participant's stimulus-response confusion matrix, with the following relation:

$$IT_{est} = \sum_{j=1}^{K} \sum_{i=1}^{K} \frac{n_{ij}}{n} \log_2 \left( \frac{n_{ij} \cdot n}{n_i \cdot n_j} \right) \quad (7)$$

where $n_{ij}$ is the number of trials that the participant identified the stimulus $i$ ($S_i$) as $j$ ($R_j$). $n_i$ is the total number of times that the stimulus $i$ is presented ($n_i = \sum_{j=1}^{K} n_{ij}$), and $n_j$ is the total count of the response $j$ ($n_j = \sum_{i=1}^{K} n_{ij}$). The equation 7 shows that the information transfer reflects the deviation of the wrong answer from the correct one. Thus, $IT_{est}$ can correctly characterize the performance of the participant's ability to identify the stimuli. In addition, the quantity $2^{IT_{est}}$ is used as a measure for the number of stimuli that can be correctly identified without error. More details on the absolute identification experiment design can be found in [33], [34].

#### 2) STIMULI

The stimuli for this experiment were 3D virtual contours with surface features (bumps) on their surface (Fig. 6). We constructed the virtual contours with non-uniform ration B-Splines (NURBS), and the number of the bumps varied between 0 and 3 ($K = 4$) [36]. We used *12*th degree NURBS curves to generate the contours, whose general equation is

$$\boldsymbol{C}(u) = \frac{\sum_{i=0}^{n} N_{i,12}(u)\, w_i \boldsymbol{P}_i}{\sum_{i=0}^{n} N_{i,12}(u)\, w_i} \quad 0 \le u \le 1, \tag{8}$$

where $\boldsymbol{P}_i$, $w_i$, and $N_{i,12}(u)$ are the control point, weight, and the *12*th-degree B-spline function, respectively. The skin-stretch interface rendered the motion of a point moving along a contour with/without the orientation adjustment. Therefore, there were two experimental conditions, one that directly renders the target 3D vectors ($A_{direct}$), and the other that reflects the skin-stretch orientation JND ($A_{JND}$).

#### 3) PROCEDURE

A total of ten participants took part in the experiment (25∼27 years old, average 26.3±0.7 years old), and two of them were female. All subjects were right-handed, and none of them hand any known problem with the sense of touch.

Before the experiment, a participant was seated in front of a monitor. S/he wore the skin-stretch haptic interface on his/her forearm along with noise reduction headphones. The experiment consisted of two experimental runs by the conditions $A_{direct}$ and $A_{JND}$. The order of the experimental condition was randomized for each participant. Prior to the main experiment, a training session was available to let a participant be acquainted with the skin-stretch stimuli and the experimental task. During the training session, the participant could see a green sphere on a random 3D contour in Fig. 6. When the participant hit the "1" or "2" key, the green sphere began to move along the contour, and the skin-stretch rendered the 3D vector matched to the motion of the sphere. Hitting "1" and "2" keys rendered the skin-stretch feedback with $A_{direct}$ and $A_{JND}$ algorithms, respectively. Once s/he was ready, the participant could move to the main experiment by hitting the enter key. As the main experiment began, white noise was played on the headphones. On each trial, one out of eight contours in Fig. 6 was selected with the same *a priori* probability, and the motion of the virtual point on the contour was presented to the participant with the skin-stretch feedback. No visual cue on the movement of the virtual point was available. After having felt the haptic stimuli, the participant answered the number of bumps that s/he felt during the trial. The stimulus and the participant's answer for each trial were recorded to form the stimulus-answer confusion matrix. The total number of trials $n$ for each experimental run was 32.

#### 4) RESULTS

Figure 7 shows the mean estimate of information transfer ($IT_{est}$) by the two experimental conditions. The mean estimates of information transfer were 0.441 bits (1.36 items) and 0.558 bits (1.484 items) for the $A_{direct}$ and $A_{JND}$ conditions, respectively. When we conducted a paired t-test, a significant difference was observed between the two experimental conditions ($t(9) = 3.035$, $p = 0.014$ for $IT_{est}$; $t(9) = 3.203$, $p = 0.011$ for $2^{IT_{est}}$). The result indicates that the skin-stretch

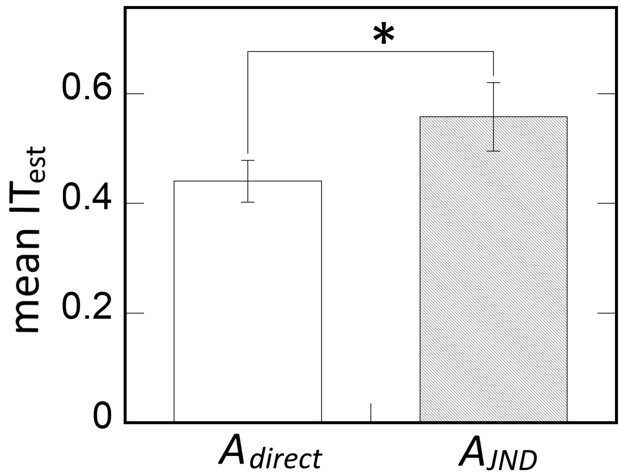


**FIGURE 7. Mean estimate of information transfer ($IT_{est}$) of Experiment 1 by two experimental conditions ($A_{direct}$: the skin-stretch algorithm that directly renders the target 3D vector; $A_{JND}$: the skin-stretch algorithm that adjusts the chain orientation based on the rotation JND data). Error bars indicate standard errors.**

orientation adjusting algorithm $A_{JND}$ improves the participants' perception of virtual surface features.

### C. EXPERIMENT 2: EFFECT OF RENDERING 3D VECTOR WITH CONTINUOUS SKIN-STRETCH FEEDBACK ON THE VIRTUAL CONTOUR FOLLOWING TASK

This subsection presents an experiment that evaluated participants' ability to move along virtual contours under two conditions. Under one condition, the haptic and visual 3D vector cues were available while there were only visual cues available in the other state. The total number of trials was 27, and each of nine virtual contours appeared three times.

#### 1) STIMULI

The experimental task for a participant was to follow a virtual contour in a 3D space, with his/her wrist. We formed a set of nine random virtual contours modeled as *8*th-degree NURBS, as shown in Fig. 8.

During the experiment, a participant wore a VIVE tracker (HTC Corp., Taiwan) around the wrist, which provide the position information. As the participant moves his/her arm, the minimum distance point on the contour to the wrist position $\boldsymbol{p}_{wrist}$ is calculated as $\boldsymbol{p}_{cont,min}$, and the target vector in 1 is

$$\mathbf{v}_{target} = \boldsymbol{p}_{wrist} - \boldsymbol{p}_{cont,min}. \tag{9}$$

The projection matrix $\boldsymbol{P}_{idx}$ in 1 is then updated by multiplying the orientation matrix $\boldsymbol{R}_{wrist}$, from the VIVE tracker. Thus, the target vector is modified as

$$\mathbf{v}_{mod,idx} = \boldsymbol{R}_{wrist}\boldsymbol{P}_{idx}\left(\boldsymbol{p}_{wrist} - \boldsymbol{p}_{cont,min}\right) \tag{10}$$

Two feedback conditions were used in the experiment: visual cues (V) and visual plus continuous skin-stretch cues (V+CF). Under both experimental conditions, the virtual

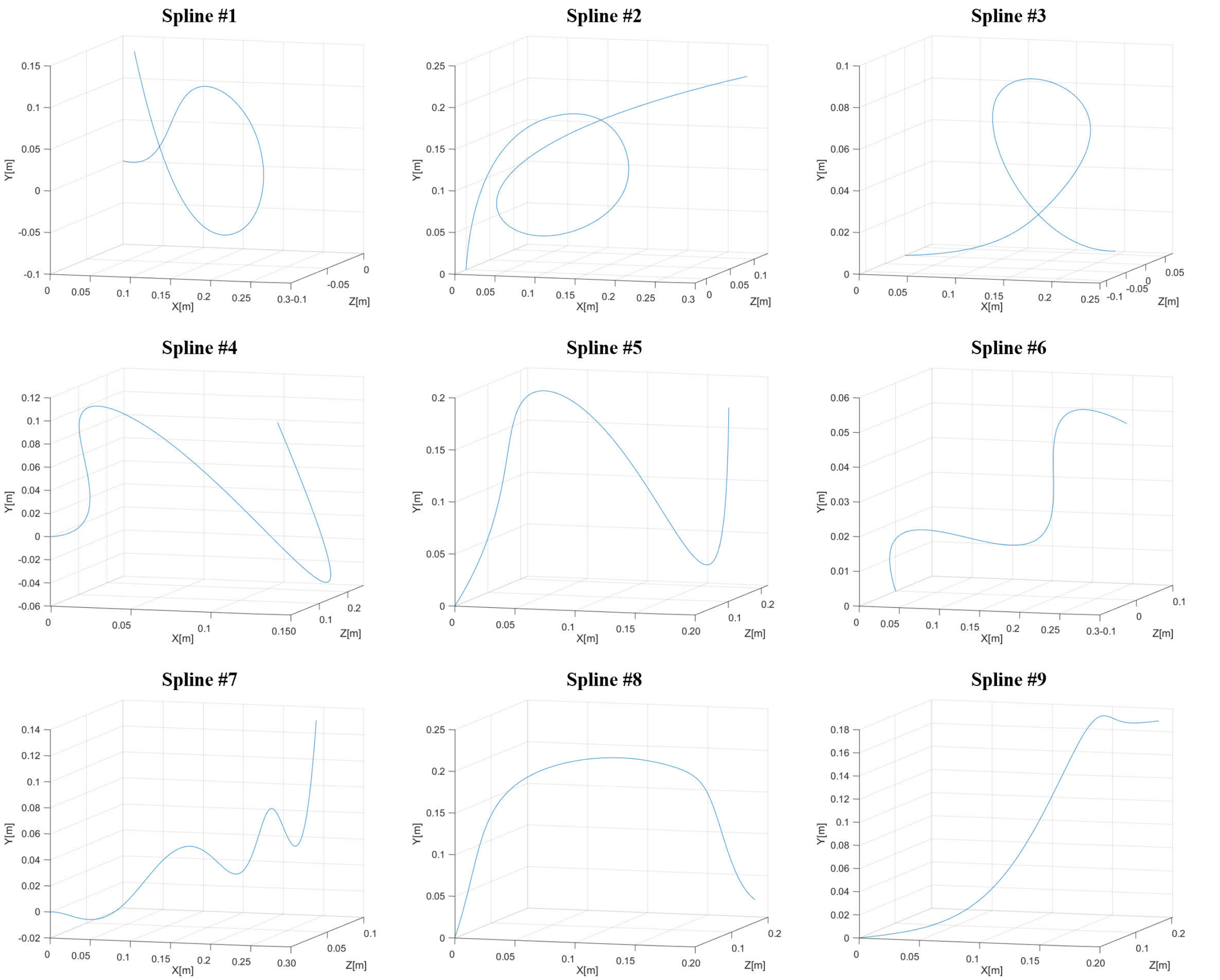


**FIGURE 8.** The virtual contour set for Experiment 2.

contours were displayed on the monitor, but the target vectors were rendered in different ways, as follows:

1) **Visual Cue (V) Condition**
(visually displays a 3D arrow to render the target vector)
2) **Visual Cue + Continuous Skin-Stretch Cue (V+CF) Condition**
(haptic-renders the target vector)

Figure 9 shows the arrow indicating the target 3D vector for the V condition. Under the V+CF condition, the target orientation of the skin-stretch stimulus in 2 is decided by considering the results of the preliminary experiment.

### 2) PARTICIPANTS

Twelve participants took part in the experiment (23∼27 years old, average 25.2±1.1 years old). Two of them were female (24∼26), and all subjects were right handed. All participants submitted the informed written consent, and none of them had any problem in tactile sensing or arm movement.

### 3) PROCEDURE

The participants of Experiment 2 were identical to those of the preliminary experiment. Before the beginning of the experiment, a participant wore a VIVE tracker on the wrist and haptic interface on his/her forearm (Fig. 9). The experiment consisted of two sessions by the experimental conditions, and they were conducted in random order. A training session was available before the experiment, where the virtual contour and the wrist position were displayed as a red curve and a green sphere, respectively. Whenever the hand moved away from the virtual contour, either visual (visual information+visual arrow) or visuo-haptic (visual information+skin-stretch cues) cue was provided to the participant. The training was terminated whenever the


FIGURE 9. Experiment Setup. The participant wore the haptic interface and VIVE tracker to conduct Experiment 1.

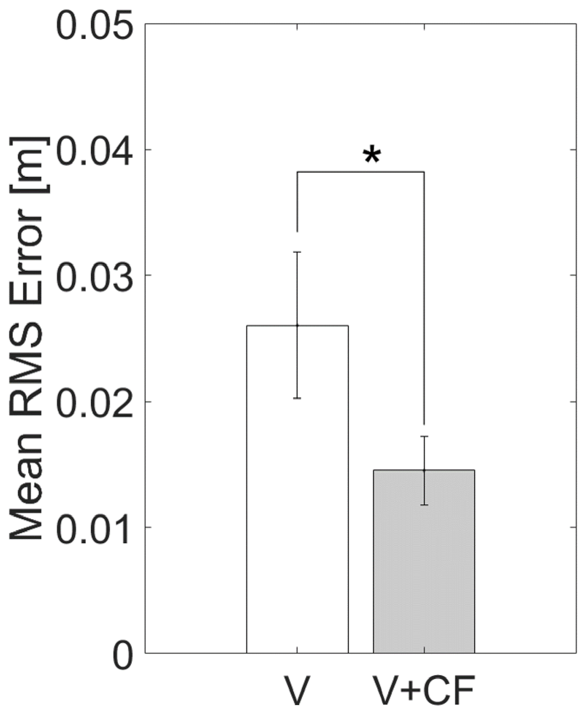


FIGURE 10. The mean RMS error of Experiment 2 by experimental condition (V: visual cue condition; V+CF: visual plus skin-stretch cue condition). Error bars indicate standard error.

participant was ready for the experiment. On each trial of the experiment, a virtual contour out of the nine samples in Fig. 6 was randomly selected. At one end of the contour, a red sphere was displayed to indicate the contour start point. Then, the participant followed along the virtual contour to the endpoint as accurately as possible. When the wrist reached the endpoint of the contour, the experiment switched to the next trial with a new virtual contour. On each trial, the root-mean-squared (RMS) error, trial time, the time when the wrist is away from the contour (error time), and the number that the wrist moved away from the contour (error count) were recorded. The minimum distance that the experimental program judged the wrist was away from the contour was 2 cm. The total number of trials was 27, and each of nine virtual contours appeared three times.

#### 4) RESULTS

Figure 10 shows the mean RMS error of Experiment 1. When we conducted a paired t-test, a significant difference was observed between the two experimental conditions ($t(11) = 2.474$, $p = 0.031$). This result indicates that the skin-stretch cue benefited the participants to conduct the contour-following task more accurately than when there were only visual cues available.

Figure 11(a) shows the mean time that each participant took for Experiment 1. The result of a paired t-test shows an insignificant difference in the mean trial time between the two experimental conditions ($t(11) = 1.444, p = 0.177$). However,

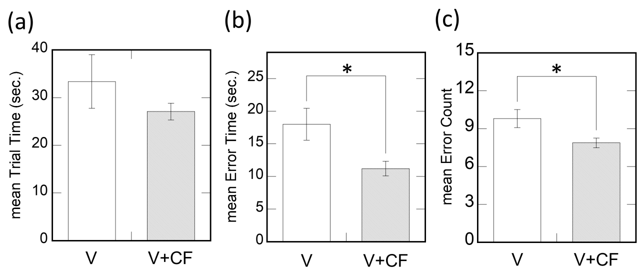


FIGURE 11. Results of Experiment 2 by experimental condition: (a) mean trial time (sec.), (b) mean error time (sec.), and (c) mean error count. The experiment program judged that a wrist was away from the contour when the distance between them was more than 2 cm. Error bars indicate standard error.

the error time was significant shorter for V+CF condition (Fig. 11(b), $t(11) = 2.497$, $p = 0.0297$). Similarly, the error count was significantly smaller when the cutaneous feedback was available (Fig. 11(c), $t(11) = 3.789, p = 0.003$). Figure 12 shows the wrist position trajectories under the two conditions along with the target reference contours. The sampled trajectory under the V+CF condition is significantly closer to the target than under the V condition. The results indicate that a participant could stay close to the virtual contour as s/he was conducting the contour following task. We found no statistically significant difference between male and female subjects for the experiment indices, including information transfer, RMS error, and experiment time.

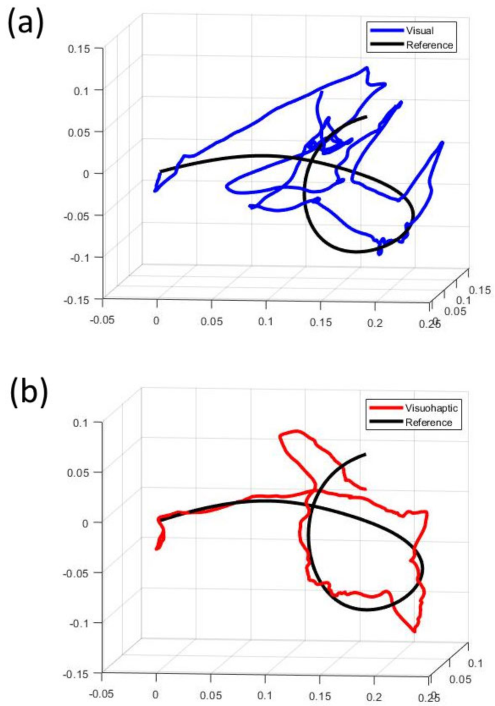


**FIGURE 12.** Examples of a participant's wrist position trajectories under the two conditions: (a) visual cue (V), and (b) visual plus continuous skin-stretch cue (V+CF) conditions. Black curves indicate the target contours.

## IV. DISCUSSIONS AND CONCLUDING REMARKS

The present study proposed a haptic system that can represent a 3D vector by combining two vectors rendered with skin-stretch haptic interfaces. By using the haptic interface, we developed a 3D vector rendering algorithm, which was optimized with the JND of rotation angle for skin-stretch feedback, measured in the preliminary experiment. Experiment 1 demonstrated that the optimized skin-stretch algorithm could enhance the perception of virtual bumps embedded in 3D contours. In Experiment 2, we tested the effect of the skin-stretch feedback to represent a 3D vector by conducting a contour-following task. The results indicated a significantly smaller RMS error with the skin-stretch feedback than when there was only visual feedback available.

The result of Experiment 1 indicated that the application of the JND data to the skin-stretch orientation improved the perception of virtual surface features. The algorithm used in the experiment applied the orientation change only when the magnitude of the change is larger than the difference threshold, whose data was collected from the preliminary test. The JND data is often used to create the effect of shading or flattening of the stimuli, while creating distortion. For instance, the JND data is often used for compression and image processing since the distortion due to the compression is invisible to the human visual system as long as it is below the JND [37]–[39]. Similarly, haptic rendering techniques, e.g., the force shading, utilize the fact that humans are less sensitive to the position change smaller than the JND to create the sensation of touching a smoothed surface [40], [41]. In contrast, few studies have proposed methods to enhance the perception of the target sensation by increasing the difference between adjacent stimuli over the JND [42]. As with the case of the image processing, the skin-stretch stimulus over the JND can cause the change of the stimulus more noticeable than the one lower than JND. Then, we can ascribe improved perception of surface feature to the increased sensitivity to the skin-stretch matched to the change of virtual surface geometry.

The significant finding of the present study is that the addition of skin-stretch could improve the contour following task with the haptic skin-stretch feedback in Experiment 2. The result can be partially explained with previous studies on the effect of haptic guidance. Findlater and Froehlich demonstrated that the guidance cue rendered with vibrotactile feedback could benefit the 2D trajectory following tasks in a series of studies [43]–[45]. Also, multiple references report that haptic feedback can improve motor tasks [46], [47]. Thus, the results of Experiment 2 and previous studies imply that humans can effectively utilize haptic feedback in motor tasks, including the 3D contour-following task, as shown in the present study. Alternatively, the improvement of the contour following with the skin-stretch feedback can explained in that our proposed method can provide the depth information. In other words, the participants may have found it difficult to keep track of their position aligned with the target contour under the control condition, which lacked the depth information. It is also notable that the additional skin-stretch feedback results in the participants' faster response (Fig. 11(b)). Overall, we can conclude that the addition of the cutaneous feedback resulted in increased geometric information of the 3D contour.

Another notable feature of the experimental results is the asymmetry of the JND by reference orientation angle, as reported in the preliminary experiment. The participants were more sensitive to the angle change when the skin-stretch feedback was aligned in the proximal-distal direction (reference angle of 90°). Such a trend can be partially explained by Johansson's early study on human sensitivity in hand by the type of mechanoreceptor. In the study, the SA II unit on the finger tended to respond to the longitudinal direction [35]. Therefore, the human sensitivity to the skin-stretch can be modeled to be asymmetric by the direction of the applied stimulus. An alternative way to explain the asymmetric sensitivity of the skin-stretch is the change of the contact area by the orientation. The deformation of the SA II unit will increase as the contact area increases. Thus, the effect of skin-stretch will be more significant when the caterpillar is aligned in the proximal-distal direction where the contact area is larger than the lateral direction.

The contribution of the present study can be evaluated in two viewpoints. The main contribution of our research is in demonstrating that haptic feedback to the hairy skin can improve the performance in a contour following task. In the previous approaches, the effect of haptic feedback for the contour following has been investigated only for the applications for a manual or hand-held haptic interfaces [46], [48]. In the meanwhile, the present study verifies that the haptic feedback applied to the forearm can also benefit the contour following task by freeing the user's hand. Next, we provide a reference to the human sensitivity to the continuous skin-stretch feedback on the forearm. Previous studies to analyze human sensitivity to the skin-stretch has mainly focused on measuring the perception thresholds for rotational skin-stretch around the dorsal side of a forearm [16], [49]. The effector to touch the skin was stationary in the studies so that they can be used for limited applications to rotate a user's skin. On the other hand, we provide a reference on human sensitivity to "continuous" skin-stretch feedback for different places around the forearm.

We demonstrated that skin-stretch feedback could benefit virtual interaction by providing 3D vector information. In future work, our study can be further supplemented in various aspects, including the skin-stretch interface design, human perception experiment, and haptic application. Regarding the haptic interface design, we are planning to optimize the number of actuators by the application. In the present study, we used four motors to render a 3D vector information, which implies that we may reduce the number of actuators. In terms of the human perception experiment, we are planning to examine the possibility if other haptic cues (e.g., vibration or mechanical stress) than the skin-stretch could have affected experimental results. Also, we plan to further investigate the validity of our proposed approach in a teleoperated robotic system. We expect that our proposed approach will effectively provide the geometry information around a robot in a remote location. Thus, a master operator will be able to avoid the collision of the robot/robot arm by perceiving the distance with a nearby obstacle rendered as a 3D vector. Additionally, we will study how well a user matches a random 3D vector rendered with our proposed method to a visually rendered vector. This will provide us another reference for how well the 3D vector rendered with skin-stretch feedback is perceived when compared to the one with visual information.

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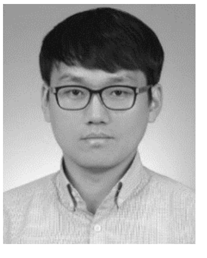

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