Two-Dimensional Moving Phantom Sensation Created by Rotational Skin Stretch Distribution

Arata Horie, Zendai Kashino, Hideki Shimobayashi, Masahiko Inami

***Abstract*— This study reports on one of the first attempts to achieve a sense of tactile motion in two-dimensions using an array of stationary rotational skin stretch elements presenting a moving phantom sensation. Herein, we propose an algorithm with two independent control parameters (the size of the stimulus area and the size of the area with maximum stimulus) for generating the moving phantom sensation using our skin stretch tactile display device. In our investigations, we first conducted an experiment to identify the relationship between the mechanical action of our device (a rotation) and the perceived stimulus intensity. Then, using the proposed algorithm, we evaluated the continuity, consistency, and position clarity of phantom sensations under several control parameters and motion direction conditions. Our results showed that both control parameters had a significant effect on the continuity of the stimulus in all directions. Furthermore, we confirmed that, using our current algorithm, the size of the stimulus area has a trade-off relation with the stimulus position clarity. We conclude the paper by discussing our findings, new control parameters that may directly determine continuity of the phantom sensation, and factors that may contribute to the consistency of stimulus intensity. This paper provides fundamental insights into the presentation of skin stretch based moving phantom sensations.**

I. Introduction

The sense of touch has a spatial component which allows us to perceive tactile motion on our skin. For example, we can perceive when an object rolls on the palm of our hand or when we are stroked on the arm or back. Reproducing or creating such experiences is an important issue for VR applications, remote manipulation, and tactile communication.

The most direct method for generating tactile motion is to actually move the end-effector over the skin (e.g., directly stroking the skin with an end-effector [1]). On the other hand, such approaches have limited the spatial scalability and expressiveness. This makes them impractical to apply in many cases, especially to large areas such as the back.

A number of researchers have realized tactile motion presentations with spatial stimulus distributions. They realize the sensation of a moving stimulus through two tactile illusions: phantom tactile sensation [2] and apparent tactile motion [3]. Choi et al. define a *moving phantom sensation* to be the creation of a tactile motion using these two tactile illusions [4]. An example of work realizing this phantom sensation is TactileBrush [5], which creates a moving phantom sensation using vibrotactile stimulus according to an algorithm to generate the sensation of a continuously moving stimuli in two dimensions.

There are many methods for presenting tactile motion using vibrotactile stimuli [5], [4], [6], [7]. However, vibrotactile stimulus is not suitable for long-term exposure. For example, prolonged exposure to vibrational stimulus leads to desensitization [8]. As people spend more time in simulated environments with simulated stimuli, there will be a need to have a method of tactile stimulus that may not suffer from a degraded experience with prolonged exposure. One candidate tactile stimulus which may be able to provide a long-term stimulus without a degraded experience is skin stretch. However, there are comparatively few works investigating phenomena such as the phantom moving sensation in the context of skin stretch stimuli [9].

Researchers have proposed a variety of devices that present skin shear deformation on various body parts [10], [11], [12], [13], [14]. Other work has aimed to present a distribution of shear deformation on larger areas of the body, such as the back [15]. Such large-area devices could benefit significantly from being able to present moving phantom sensations as it significantly increases its freedom of expression.

There is a high likelihood that a moving phantom sensation can be generated by controlling the skin stretch stimulus intensity distribution over an area of skin. Past work has shown that modulating vibration stimulus intensity is a good approach for presenting a continuous moving phantom sensation [7]. This suggests that modulating stimulus intensity could be used as an approach for presenting a moving phantom sensation in other kinds of tactile stimuli. Recent works producing continuous tactile motion using normal force [16] and displacement [17] show that tactile sensations other than vibration have the potential to generate moving phantom sensations. Since skin shear deformations have a wider dynamic range of perceptual intensity than normal displacements [18], a moving phantom sensation of skin stretch might be induced taking a similar approach.

Past work has reported on generating a moving phantom sensation using rotational skin *shear* stimulus elements which slip on the skin [19]. However, to our knowledge, there is no report showing that the moving phantom sensation can be induced using rotational skin *stretch* without slip. As such, it is not clear how the rotation angles of multiple actuators should be controlled in order to induce a moving phantom sensation. Furthermore, it is not clear how qualities of the stimulus, such as continuity and position clarity, might be affected by the actuator control parameters.

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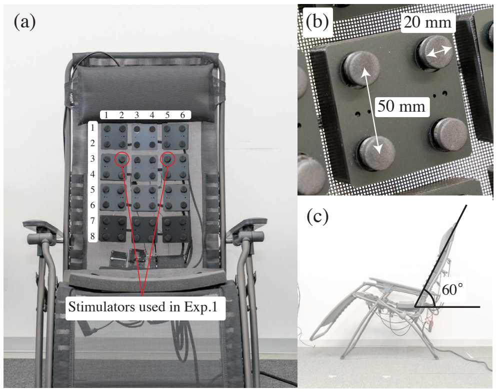

Fig. 1. (a) Apparatus overview. (b) Close up picture of one module. (c) The slant of the back was 60° from horizontal.

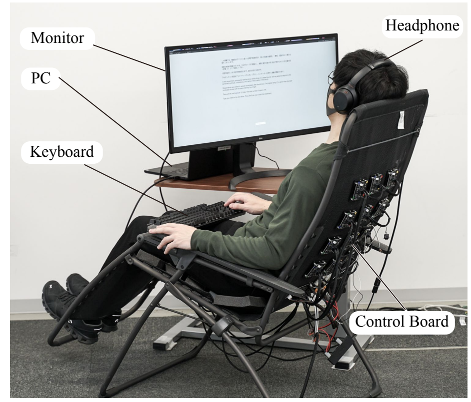

Fig. 2. Experimental environment

Herein, we report on an investigation into the presentation of a two-degree-of-freedom(DoF) moving phantom sensation using rotational skin strech distribution stimuli. First, we provide basic information about the apparatus used in the experiments. Then, we describe the method and result of experiments conducted to relate actuator rotation angle to perceived skin stretch intensity. Finally, we propose an algorithm for presenting a moving phantom sensation with two-DoF with two independent control parameters and evaluated it through experimentation. Through this evaluation, we determined how the two control parameters influence the perceived sensation in terms of continuity, consistency, and position clarity of the stimuli.

II. Experimental apparatus

We employed a two-dimensional large-area haptic display system to investigate moving phantom sensations of skin stretch. The hardware of this system consists of an array of skin stretch presentation elements, embedded in modules attached to a chair, controlled by a computer through a control board. Fig. 1(a) shows the haptic display and one module containing four stimulus elements. Each element rotates to deform the skin on the user's back and generate a large-area spatio-temporal strain pattern.

Each skin stretch presentation module consists of a set of tactors, attached to servo motors, and a holding apparatus as shown in Fig. 1(b). Each tactor is a chloroprene rubber sponge with a diameter of 20 mm and a thickness of 5 mm. We chose this material because it lacks sharp edges and has a high coefficient of friction. These properties prevent pain by avoiding focal pressures and slipping of the tactors respectively. As noted above, each tactor is mounted directly on the head of a servo motor to allow it to rotate in place.

The servo motors (RS204MD, Futaba) have a maximum rotational torque of 2.1 Nm and are held together in the holding apparatus. The maximum rotational angle of the servo motor is 300°, which is enough for provide skin deformation. The holding apparatus was 3D printed to keep a distance of 50 mm between tactors, which is around the two-point discrimination threshold of the human back [20]. This system we used in this study had 12 modules with 4 servomotors each, for a total of 48 stimulus elements. The back support of the chair is capable of reclining and can be fixed at an angle of 60° using a jig we made. The back of the chair is a mesh such that, when the user puts its weight on it, the modules passively tilt and the tactors conform to the curved surface of the body.

All of the motors are controlled by a PC through a set of custom made control boards. Each module has an independent control board (HPF001, karakuri products) which provides power and sends serial commands to the four motors. A distribution board allows for all twelve control boards simultaneously receive power and communication from the control computer. The control software was developed using Unity (Unity 3D). The software determines the rotation angle of each motor and sends them to the distribution board at 60Hz. Unity was also used to display questions and collect answers from participants during the experiments.

III. Preliminary Study: The Perceptual Intensity of Rotational Skin Stretch

In this experiment, we sought to establish a relation between stimulus intensity and the magnitude of rotational skin stretch presented by our apparatus using Stevens' law. This served as preliminary validation that we could present a controllable stimulus using the apparatus.

A. Method

We conducted the experiment following the general magnitude estimation protocol.

1) Participants: Ten male students (22-30 years old with an average age of 24.5; one of them left-handed) participated in this experiment. No skin diseases were reported.

2) Stimulus: The stimulus in each trial was the rotation of a single motor located in the middle-left or middle-right of the back. The motors used in this experiment were $S_{2,3}$ and $S_{5,3}$ highlighted in Fig. 1(a). Both motors rotated clockwise from their initial position. The rotation angle was controlled according to the five profiles shown in the Fig. 3. Each stimulus had different maximum angle between 10° to 50°. The all stimuli duration were same. Each trial had a reference stimulus, the 30° curve in Fig. 3, and a test stimulus presented one after another to the same position.

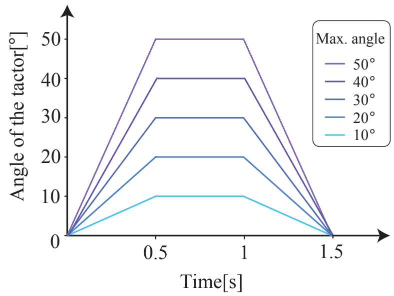

Fig. 3. The rotation angle profiles in the preliminary study.

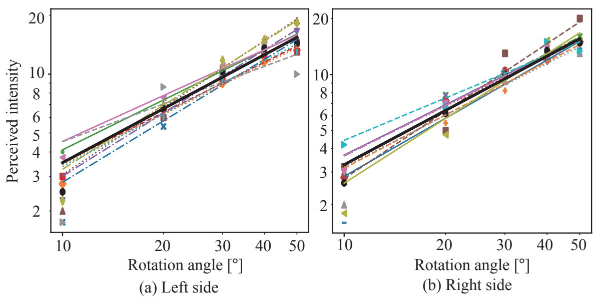

Fig. 4. The result of the preliminary study plotted on logarithmic axes.

3) Procedure: Each experiment began with the operator explaining the experimental procedure to the participant. After receiving an explanation, the participants were asked to wear the prescribed shirt (SOFT TOUCH CREW NECK T, UNIQLO). Participants wore the shirt directly on their skin. Next, the participant was seated in the apparatus, which was tilted to 60° as shown in Fig. 1(c) by the operator and fixed in place. A monitor was then placed in front of the participant used to present instructions during the experiment. The experimental environment is shown in Fig. 2. Once the environment was set up, instructions on what to do during the experiment were given to the participant.

The participant was told that a test stimulus would be presented after a reference stimulus. They were then asked to provide an integer representing the intensity of the test stimulus relative to the reference stimulus assuming the reference stimulus had an intensity of 10. The participants were asked to use a keyboard to give their responses. The keyboard was placed on their legs so that their posture would not change when giving a response. Each participant experienced a total of 40 trials; four repetitions for each of ten test stimuli (five types, two locations). The order of the trials was randomized and a break of at least one minute was taken once every ten trials. The duration of the experiment was about twenty minutes, including breaks.

B. Result

The results of the experiment are shown in Fig. 4. The colored points correspond to responses given by the participants. Both graphs show that the perceived intensity tends to increase with the size of the rotation angle, suggesting that the stimulus intensity can be controlled by the rotation angle.

Stevens' law is an established method for modeling the relation between physical and perceptual intensity:

$$\psi = k\phi^{\alpha} \tag{1}$$

where ψ is the perceived intensity, ϕ is the physical quantity of the stimulus, α is the intrinsic power exponent for the perceptual modality, and k is a constant of scale. Fitting the data we obtained gave us a model for how rotation angle relates to the perceived stimulus intensity. Each dashed line in Fig. 4 represents the fit for each participant while the solid black line is the fit to the average responses. In detail, fitting (1) to the average of the responses across participants gives:

$$\psi_{Left} = 0.4279\phi^{0.9162} \quad (R^2 = 0.9787) \tag{2}$$

$$\psi_{Right} = 0.3532\phi^{0.9684} \quad (R^2 = 0.9660) \tag{3}$$

The similarity between the two functions shows the reproducibility of the result. Therefore, it is suggested that the stimulus elements in this system can provide controllable stimulus intensity.

IV. Two Dimensional Moving Phantom Sensation by Rotational Skin Stretch Distribution

In this section, we first present our novel control algorithm, with two control parameters, for generating moving phantom sensations using multiple stationary rotational motors. Then, we present a user study we conducted to investigate how stimuli generated by our algorithm are perceived by users under a range of control parameter conditions.

A. The Proposed Control Algorithm

The proposed control algorithm generates a distribution around a center point, which we call the *virtual stimulus point*, S_V as shown in Fig. 5(a). Each tactor's rotational angle, $\theta_{i,j}$, is a piecewise continuous function of the distance, $d_{i,j}$, between the tactor position, $S_{i,j}$, and S_V:

$$d_{i,j}(S_V, S_{i,j}) = |S_V - S_{i,j}| \tag{4}$$

$$\theta_{i,j}(d_{i,j}) = \begin{cases} \theta_{max} & (d_{i,j} \leq D_m) \\ \theta_{max}\dfrac{D_s - d_{i,j}}{D_s - D_m} & (D_m < d_{i,j} < D_s) \\ 0 & (D_s \leq d_{i,j}) \end{cases} \tag{5}$$

Here, D_s and D_m are two control parameters which defined the shape of this function and θ_{max} is the maximum rotation angle of the stimulus elements. D_s is the distance within which the rotation starts, while D_m is the distance within which the rotation angle is held at its maximum. Fig. 5(b) shows $\theta_{i,j}(d_{i,j})$ with the control parameter values shown on the horizontal axis.

B. User Study

To investigate the qualities of the stimulus generated by our algorithm, we used it to control the experimental apparatus described in Section II. In this study, users experienced various stimuli and we used their subjective perception of the stimulus to identify how users perceive the stimulus generated under various control parameter conditions.

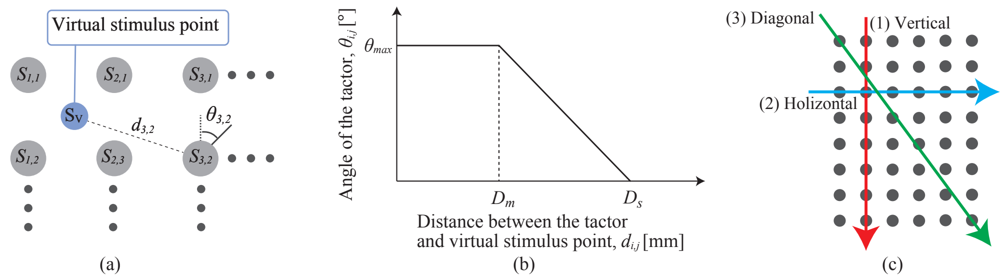

Fig. 5. (a),(b)The algorithm defines the rotation angle of a tactor based on the distance between virtual stimulus point and the tactor. (c)The trajectories of the virtual stimulus point in experiment 2

1) Participants: Ten male students, the same as those who participated in the preliminary study, participated in this study.

2) Procedure: The initial steps setting up the experimental environment in this study were identical to those in the preliminary study. The system presented stimuli to the participant after they were seated in the apparatus and received the explanation. The participants then evaluated the a) continuity, b) consistency, c) position clarity of the stimulus on a 7-point Likert scale.

Continuity and consistency are often used as indicators in conventional researches to evaluate the quality of phantom sensation [6], [19], [21], [22]. Additionally we evaluated position clarity because we believe it is important indicator for application which provides exact position of stimulation point in the body. The participants rated the maximum 7 as equivalent to the sensation of actually being traced on the back with same force. The participants responded using the mouse on the desk and pressed the return key on their lap to continue the trial.

In the experiments described below, the control parameters, D_s and D_m, were set to 50, 70, 90 mm and 0, 20, 40 mm, respectively. The maximum angle, θ_{max} was set to 40°, as Experiment 1 identified that participants could perceive sufficient intensity variation between rotation angles of 0 and 40°. Finally, to investigate any directional dependence of the moving phantom sensation, we chose to move the virtual stimulus point in the three directions shown in Fig. 5(c). The velocity of the moving virtual stimulus point was aligned in all conditions and was 165 mm/s. Investigating three directions, three D_s values, and three D_m values made for a total of 27 conditions we investigated (3 x 3 x 3).

The order of trials was randomized to eliminate any ordinal effects. The 27 stimuli were repeated 5 times, for a total of 135 trials. Participants were given a break of at least 1 minute every 10 trials, and the experiment lasted about 1 hour include breaks.

C. Result

Fig. 6 shows the results of the experiment. The 3 × 3 graphs matrix is ranged based on each presentation directions(Vertical, Horizontal, Diagonal) and questionnaire items(Continuity, Consistency, Position clarity). The horizontal axis is D_s, the vertical axis is the participants responses.

TABLE I

STATISTICAL ANALYSIS RESULTS OF EXPERIMENT 2

(a) Continuity	D_s	D_m	Interaction
Vertical	$F(2,81) = 60.7$ **$p < 0.001$**	$F(2,81) = 13.9$ **$p < 0.001$**	$F(4,81) = 2.9$ **$p = 0.021$**
Horizontal	$F(2,81) = 63.9$ **$p < 0.001$**	$F(2,81) = 11.9$ **$p < 0.001$**	$F(4,81) = 8.5$ **$p < 0.001$**
Diagonal	$F(2,81) = 40.5$ **$p < 0.001$**	$F(2,81) = 18.7$ **$p < 0.001$**	$F(4,81) = 8.7$ **$p < 0.001$**
(b) Consistency	**D_s**	**D_m**	**Interaction**
Vertical	$F(2,81) = 1.59$ $p = 0.213$	$F(2,81) = 0.68$ $p = 0.508$	$F(4,81) = 0.13$ $p = 0.969$
Horizontal	$F(2,81) = 0.50$ $p = 0.606$	$F(2,81) = 0.18$ $p = 0.832$	$F(4,81) = 0.36$ $p = 0.833$
Diagonal	$F(2,81) = 0.98$ $p = 0.378$	$F(2,81) = 1.58$ $p = 0.211$	$F(4,81) = 0.53$ $p = 0.709$
(c) Position clarity	**D_s**	**D_m**	**Interaction**
Vertical	$F(2,81) = 29.4$ **$p < 0.001$**	$F(2,81) = 0.35$ $p = 0.705$	$F(4,81) = 0.46$ $p = 0.759$
Horizontal	$F(2,81) = 14.3$ **$p < 0.001$**	$F(2,81) = 0.22$ $p = 0.799$	$F(4,81) = 0.45$ $p = 0.765$
Diagonal	$F(2,81) = 6.97$ **$p = 0.002$**	$F(2,81) = 0.30$ $p = 0.740$	$F(4,81) = 0.08$ $p = 0.988$

Each color shows each D_m condition. Plotted dots shows the averaged scores of participants answers in each conditions and the vertical lines indicate the 95% confidence interval. As an overall trend, the graph shows a similar trend regardless of the direction, suggesting that the similar sensation can be achieved for each direction with two-DoF.

In all the presentation directions, the perceived level of continuity has a positive relation with D_s. It can also be observed that the scores of continuity varies with D_m. We applied a two-way repeated-measures ANOVA to the continuity scores and the results is shown in Table I(a). We observed that D_s and D_m had significant effects on the continuity scores. The interaction between D_s and D_m also had significant effect.

The scores of position clarity have a negative relation to D_s in all presentation directions and did not change according to D_m. We applied a two-way repeated-measures ANOVA to the position clarity scores and the results is shown in Table I(c). We observed that D_s had significant effects on the position clarity scores. On the other hand, D_m and interactions between the two parameters has no significant

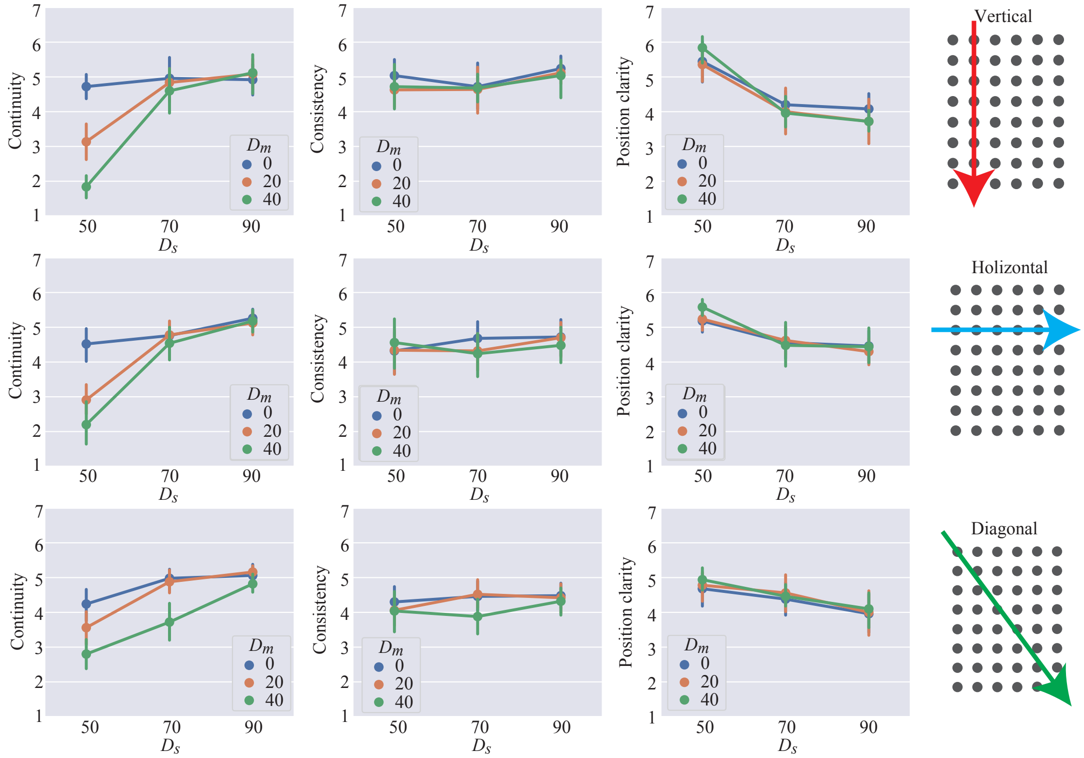

Fig. 6. The results of experiment 2. Each row shows stimulus direction, and each column shows evaluated item.

effect.

In all presentation directions, the consistency score was almost flat and was unaffected by D_s or D_m. The score remained in the middle, around four to five, suggesting that something other conditions than the parameters in this experiment determines the force consistency. We applied a two-way repeated-measures ANOVA to the force consistency scores and the results is shown in Table I(b). Both D_s and D_m had no significant effect. We also applied a one-way repeated-measures ANOVA to investigate the effect of the presented direction. The result showed that direction had significant effect ($F(2, 18) = 4.1, p = 0.03$). We ran Tukey-Kramer post-hoc analysis on the direction conditions and observed a significant difference between the Vertical-Horizontal conditions ($p = 0.023$) and Vertical-Diagonal conditions ($p < 0.001$).

V. Discussion

Through our experimental results, we verified that both the length of the upper and lower edges of the trapezoidal profile are parameters which influence the continuity of the moving phantom sensation. This suggests that the phantom sensation of continuous movement is affected by some parameter that combines D_s and D_m. One example of a parameter which is influenced by both D_s and D_m is the slope of the trapezoid. This slope, K, can be obtained by:

$$K = \frac{\theta_{max}}{D_s - D_m} \tag{6}$$

where θ_{max} is the maximum angle of rotation, 40° in our experiment. Analyzing the data, we found that the continuity scores between conditions where K are similar tend to be close. Therefore, we plan to investigate whether continuity can be controlled by K in future work.

The experimental results also indicated that there is a trade-off between continuity and position clarity when using the parameters adopted in this paper. A wider stimulus area makes it harder to locate the stimulus point while a narrower stimulus area makes it less continuous. Changing parameters may, however, allow for us to achieve stimulus which is both continuous and easy to localize. For example, we may be able to use the slope parameter, K, to directly control continuity while controlling position clarity through D_s.

In contrast continuity and position clarity, the consistency of the stimulus intensity was not affected by D_s and D_m. This suggests that a sense of consistency may be determined by parameters not considered in the proposed rotation angle algorithm. The fact that significant differences in consistency were found in the Vertical-Horizontal and Vertical-Diagonal conditions suggests that some directions crossed areas with different perceived intensities. This may have been due to either uneven pressure applied to the back or variations in sensitivity between participants. One 28-year-old male who participated the pressure distribution measurement found that the pressure of the tactor near the spine was weak. Since mechanoreceptor activity correlates with strain energy density [23], [24] (the sum of vertical and shear strain energy density) a difference in pressure would result in a different stimulus intensity, even when the same shear rotation angle is presented. Several approaches could be taken to improve the consistency of the stimulus intensity: 1) Use a device which realizes a uniform pressure distribution, 2) Measure and map the perceived intensities presented when the tactors rotate. The first approach would require equalizing the pressure applied to the skin from the tactors. For example, we could select passive mechanisms, such as a rocher bogie [25], or active pressure optimization mechanisms with pressure sensors and additional actuators. The second approach is to derive the model of the relationship between rotation angle and perceived intensity for multiple points on the back and control perceived intensity rather than physical rotation. The second approach has been taken by Yun et al. in their study inducing a moving phantom sensation using discrete vibration actuator [6]. This approach may be effective in our case as well, since the approach can eliminate perceived intensity differences caused by any sources, including pressure.

VI. Conclusion

In this study, we proposed an algorithm for presenting a two-DoF moving phantom sensation using a stationary array of skin stretch stimulus elements and reported on how the algorithm's control parameters affect the quality of experience. We conducted experiments investigating the effect of the control parameters using a chair-type device with 48 independently rotating tactors working to present a skin stretch distribution on the user's back. To identify the appropriate control parameters, we first conducted the magnitude estimation procedure to identify the relationship between the perceived stimulus intensity and the tactor rotation angle. The results showed that the stimulus intensity can be controlled for angles up to 50° of rotation. Then, we conducted an extensive study exploring how two control parameters determining the size of the stimulus region and the size of the region keeping maximum rotation angle affected the sensation generated by the algorithm. In this study, we focused on evaluating how the control parameters influenced the continuity, consistency, and position clarity of the moving phantom sensation generated by the stimulus. The results showed that the parameters we proposed had a significant effects on continuity and position clarity. Furthermore, we identified that, given our current parameters, continuity and position clarity have a trade-off relation. Given these results, we discussed several new control parameters which could be tuned to create a sensation which has both high continuity and position clarity. We additionally considered what parameters might affect the consistency of stimulus intensity and provide ideas on how to deliver a more consistent stimulus. These findings and our discussions can serve as a reference when designing skin stretch distribution stimuli with the objective of inducing a moving phantom sensation.

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