Voluminous Fur Stroking Experience Through Interactive Visuo-Haptic Model in Virtual Reality

Juro Hosoi, Du Jin, Yuki Ban, and Shin'ichi Warisawa, *Member, IEEE*

***Abstract*—The tactile sensation of stroking soft fur, known for its comfort and emotional benefits, has numerous applications in virtual reality, animal-assisted therapy, and household products. Previous studies have primarily utilized actual fur to present a voluminous fur experience that poses challenges concerning versatility and flexibility. In this study, we develop a system that integrates a head-mounted display with an ultrasound haptic display to provide visual and haptic feedback. Measurements taken using an artificial skin sheet reveal directional differences in tactile and visual responses to voluminous fur. Based on observations and measurements, we propose interactive models that dynamically adjust to hand movements, simulating fur-stroking sensations. Our experiments demonstrate that the proposed model using visual and haptic modalities significantly enhances the realism of a fur-stroking experience. Our findings suggest that the interactive visuo-haptic model offers a promising fur-stroking experience in virtual reality, potentially enhancing the user experience in therapeutic, entertainment, and retail applications.**

***Index Terms*—Fur, hair, haptic display, mid-air haptics, virtual reality.**

I. Introduction

HAPTICS plays a crucial role in human cultural and social activities. Studies on haptics consider various perspectives: perception, sensing, and feedback. Particularly, the touch of fur, such as that of animals, is comfortable and there is a demand for stroking and touching fur in our daily lives [1], [2]. The experience of touching fur or animals has been utilized in various applications including robots and furniture to evoke a sense of closeness and comfort [3], [4], [5], [6]; entertainment; animal-assisted therapy [7], [8], [9], [10]; treatment for overcoming animal phobias in virtual reality (VR) applications [11]; and online shopping for clothing, towels, and interiors [12], [13], [14].

Various studies have been conducted to create the experience of touching fur. The methods used can be broadly divided into two approaches. The first involves the use of real fur. Wada et al. introduced three furry animal robots in a health service facility to improve the mood and depression of elderly people [4]. Lee et al. developed a mechanism for grasping brush hairs, allowing manipulation of fur characteristics such as angle and height [15]. These methods employing actual fur offer high levels of realism. However, the specific properties of prepared fur, such as density and fineness, should match the intended display. Further, existing methods lack versatility because they require precise alignment of position, orientation, and shape to match the intended content. The second approach involves simulating the tactile experience of fur without using actual fur. Physical constraints can be reduced by simulating contact with fur, thereby facilitating various applications. Lin et al. conducted the studies on electrical stimulation by touching the surface of a computer graphics (CG) cat [16]. In their research, the simulation of contact with a flat-textured cat surface can be achieved. However, to the best of our knowledge, prior research has not successfully presented the tactile sensation of voluminous and soft fur, while popular types of fur that are reported to offer a highly pleasant experience, such as long-pile fabrics, the fur of animals like cats and dogs, or human hair, are often voluminous and soft [1], [2], [17], [18].

This study aims to simulate the tactile experience of stroking voluminous fur. In this paper, we define "voluminous fur" as fur with long hairs that exhibit directional alignment, such as following the natural growth pattern. Voluminous fur differs from flat textures because it possesses shape and direction, and exhibits different deformations and tactile sensations based on hand movements and fur conditions, resulting in varied tactile sensations. Based on these features, we propose an interactive visuo-haptic model to present a fur-stroking experience.

Challenges associated with replicating the tactile experience of voluminous fur without real fur are primarily attributed to two factors. First, rendering spatial simulations using devices such as pin arrays [19] is nearly impossible without actual fur. Second, voluminous fur is much softer than human skin and is registered as a subtle tactile sensation. Therefore, rigid haptic devices such as vibrators [20], [21] compromise the delicate feeling of fur. Thus, we use mid-air ultrasound haptic feedback to provide tactile stimuli without contact. Furthermore, we use cross-modal illusions with fine CG hair models for precise spatial mapping.

First, we develop a measurement system using an artificial skin sheet to mimic the experience of stroking, thereby enabling the observation of voluminous fur characteristics. Our measurements reveal that visual and tactile responses exhibit anisotropy depending on the stroke direction. Using measurement results,

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This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by Research Ethics Committee of the University of Tokyo under Application No. 23-559.

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we develop tactile and CG models that present fur texture characteristics in response to hand movements, and construct a system to present these models using an ultrasound haptic display array and a head-mounted display (HMD).

This study verifies whether an interactive model using combined visual and haptic feedback related to hand movements can replicate the experience of stroking voluminous fur. In Experiment 1, we assess the effect of our tactile design on evoking fur-stroking sensation, focusing solely on haptic stimuli to eliminate potential anticipatory biases. Experiment 2 explores the closeness of our proposed interactive visual and haptic models in reproducing fur-stroking sensation compared to actual fur. This paper is a revised version of the abstract demonstrated at SIGGRAPH Asia 2023 [22]. We have incorporated more detailed measurements and models. We conducted two additional experiments to examine the effectiveness of the proposed method.

II. Related Work

A. Fur Display

The tactile experience of touching fur has profound significance across various domains. For example, therapeutic robots with fur have been used in health service facilities to improve the mood of elderly people [4]. Fur-covered furniture at home has been demonstrated to increase pleasantness and comfort [3]. Furry animals, such as dogs and cats, have been used extensively in animal-assisted therapy to improve emotional well-being [8].

Previous studies on fur displays predominantly used real fur. Furukawa et al. designed a fur interface with a bristling effect using a piece of real fur equipped with vibrational motors [23], [24]. Lee et al. proposed a handheld fur display that presented different stiffness, roughness, and surface height by controlling fur length and bending fur direction [15]. Nakajima et al. integrated plastic fiber optics into a fur display to provide visual feedback in addition to tactile sensations during interactions [25]. Although the use of real fur can provide the most realistic tactile sensation, systems become less adaptable because the fur properties are restricted to those of the fur used. In addition, if such a type of fur display is used to provide haptic feedback of a virtual furry object in VR, the exact positioning, orientation, and shaping of real fur require adjustment in real time to correspond with the intended effect. Generally, such a feature is not feasible for several interactive applications such as petting a moving virtual animal.

A study presented fur tactile sensation without the use of real fur or fur-like devices. Instead, a wearable electro-tactile rendering system was designed to simulate the tactile sensation of stroking a furry cat using electrical stimulators on a haptic glove [16]. However, fur was treated as a flat-textured surface, and the complex properties of fur and its interaction with the hands of the user in 3D space were not considered.

Our proposed method fills the research gap by presenting voluminous fur tactile sensations without the use of real fur while considering complex fur properties and 3D interactions based on a kinematic model elicited from real fur.

TABLE I
List of Textures That Have Been Presented Using Mid-Air Ultrasound Haptic Feedback

Steam	Water	Cloth	Gel	Skin	Cork
[31, 63]	[30, 31, 61] [62, 63]	[60, 65]	[60]	[64]	[61, 65]
Wood	**Metal**	**Ice**	**Brick**	**Paper**	
[60]	[61, 65]	[32]	[65]	[65]	

B. Ultrasound Haptic Feedback

Ultrasound haptic devices have emerged as promising solutions for providing touch sensations without direct physical contact. These devices use focused sound waves to provide multi-point stimulation across a large area with high temporal and positional accuracy, enabling unique tactile experiences that are not possible with other technologies [26].

Since the introduction and evaluation of ultrasound haptic in 2008 [27], it has been extensively used in virtual user interface components to enhance gesture input interactions. For example, Sand et al. installed an ultrasonic phased array on an HMD to provide tactile feedback when pressing a button on a virtual keyboard [28]. The participants in their user study unanimously found the feedback preferable. Harrington et al. used ultrasound haptic feedback for a slider bar in a driving simulator, which resulted in the shortest interaction time and the highest number of correct responses [29]. For such types of interactions, the existence of haptic feedback is more important than how it feels, as the main purpose is to confirm to users that the system is reacting to their input [26]. Thus, ultrasound haptic feedback is a popular choice owing to its flexibility and non-contact nature.

Recently, the technology has been used to simulate complex haptic sensations in the real world. Jang et al. developed a fluid tactile rendering method using an ultrasound haptic display and smoothed-particle hydrodynamics to provide realistic vibro-tactile feedback for virtual fluid interactions on the hands of users [30]. Singhal et al. integrated heat modules with an ultrasound haptic display in an open-top chamber to generate thermos-tactile feedback resembling steam or campfire [31]. Motoyama et al. presented a non-contact cooling sensation using ultrasound-driven mist vaporization [32]. Such studies suggest that the capacity of ultrasound haptic feedback can be further expanded using appropriate modulation methods and complementary modalities. However, most previous studies compare only the presence or absence of ultrasound haptic stimulation or rely on predefined, static parameters [26], [28], [29], [31], [33]. The methods and effects of interactively modulating ultrasound feedback in response to hand movements and environmental changes remain largely unclear. Our proposed haptic model capable of adapting to complex interactions with fur has the potential to advance knowledge in the field of mid-air ultrasound haptic display.

As shown in Table I, which summarizes the textures presented through ultrasound haptic feedback in previous studies, various materials, primarily soft ones, have been explored. However, the tactile sensation of fur remains unexplored, and this research focuses on the presentation of the tactile sensation of

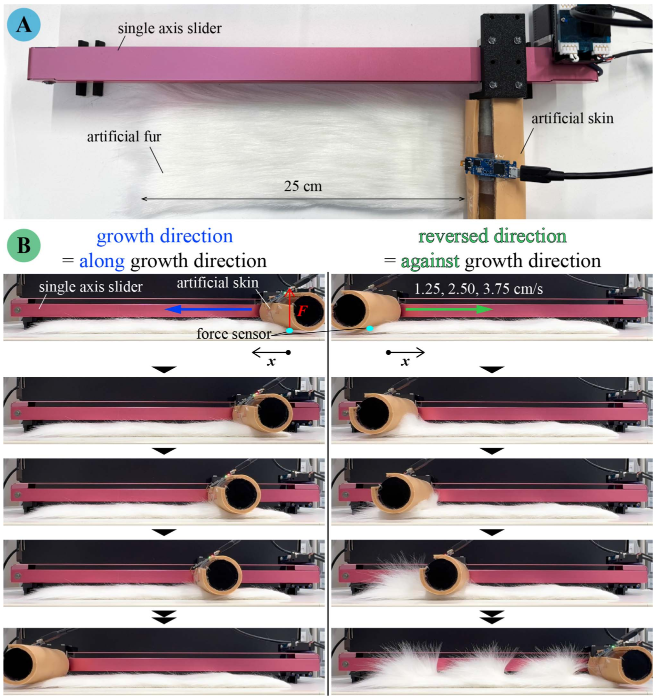

Fig. 1. (a) Top view of the measurement system for observing visual behavior and resistive force when stroking fur of width 25 cm. (b) Side view of the measurement system stroking voluminous fur. Two vertical rows of pictures show the transition of visual behavior when the fur is stroked along and against the growth direction, respectively.

voluminous fur. We anticipate this novel application to broaden the scope and applicability of ultrasound technology in immersive environments.

III. Approach

To design a visuo-haptic model for stroking voluminous fur, measuring the visual characteristics and reactive forces involved is crucial. Although previous research has focused on measuring the normal force of a single hair or short fur [34], [35], [36], [37], sufficient measurements have not been conducted for voluminous fur. Therefore, we conducted measurements on behavior while stroking voluminous fur on artificial skin for this study. Subsequently, leveraging these observations, we constructed visual and haptic models of voluminous fur.

A. Measurement System and Procedure

To investigate visual and haptic behaviors during voluminous fur-stroking, we developed a measurement system by referencing a sensor system that measures the force of hair strands [38], [39], [40]. Fig. 1(a) shows the top view of the measurement system. The measurement system comprised a cylindrical resin (diameter: 30 mm) equipped with an artificial skin sheet (Shore A hardness: 10–15 mm; thickness: 4 mm) to simulate skin deformation. This 4 mm thickness was chosen based on statistical data for human skin thickness [41], providing adequate deformation to observe the interaction with soft and voluminous fur. A force sensor (8 mm diameter sensor 1 N, SingleTact) was integrated due to its thin, high-sensitivity structure, suited for capturing the soft, voluminous fur. Given the sufficiently large dimensions of the sensor relative to the fur's fine hair, we determined that a single-point measurement would yield a reliable average response. The measurement system also includes a single-axis motor (PCS9S-330-S330, THK) to control movement of the artificial skin and artificial fur (hair length: 5 cm; fur width: 25 cm).

We positioned the force sensor 1 cm above the lower edge of the fur and moved it in two horizontal directions, growth and reversed directions, at 1.25 cm/s, 2.50 cm/s, and 3.75 cm/s. We recorded the visual response using a camera and measured the normal force using the force sensor. Before each movement, we ensured uniformity of the fur texture by combing it. In addition, additional measurements were taken at a speed of 3.75 cm/s for all three equidistantly spaced directions between the forward and reverse directions, and the results are included in the Appendix.

B. Observations of Visual Behavior

First, we discuss the visual characteristics of voluminous fur based on our observations. Fig. 1(b) illustrates the temporal changes in fur when stroked in two directions. The left column represents the behavior when stroked along the natural direction of growth, whereas the right column represents the behavior when stroked against the growth direction of fur. As shown in the figure, the visual behavior of fur varied during and after the stroke, depending on the stroke direction. However, little difference in visual behavior was observed depending on stroke speed.

When using a slider to stroke hair strands, it is known that the behavior of the hair can be divided into two primary phases: the deformation phase and the rubbing phase [37]. During the deformation phase, the slider lays down and bends the hair. In the rubbing phase, the slider rubs upon the bent hair. In this study, for fur with a high density of hairs, this behavior is expected to occur continuously.

When stroked along the growth direction, the fur strands were compressed by the moving artificial skin. Subsequently, the fur strands regained their original shape after the skin passed over them. Consequently, minimal visible traces remained after the stroking motion. Conversely, when voluminous fur was stroked against its growth direction, the fur bundles that were initially in contact with the hand were gradually lifted to the opposite side and they started to curl, involving other fur bundles along the stroke path. As the experiment progressed, the bent fur bundles were released and the skin made contact with the next bundle that was lifted. The released bundles maintained their curled shape, and the repetitive process left cyclic traces of stroking. The unique behavior of maintaining a curled shape has been noted in previous research for potential applications in visual displays [42], [43], [44].

C. Measurement Results of Resistive Force

We examined the normal forces measured alongside visual behavioral observations. Fig. 2 shows the results of the vertical forces measured in multiple stroke directions and speeds. The x-axis represents the stroke position relative to the point where

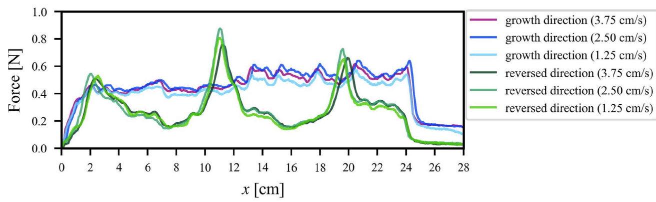

Fig. 2. Results of the measured vertical force when the force sensor comes in contact with the fur at the point designated as $x = 0$. The horizontal width of fur is 25 cm. Each line in the graph represents six distinct conditions, a combination of three velocity conditions and two movement direction conditions.

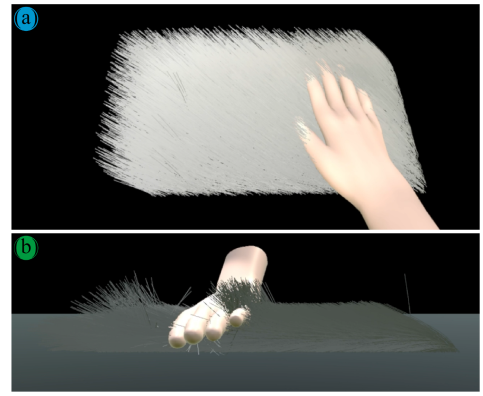

Fig. 3. (a) Top view of the implemented fur CG model stroked in the growth direction. The fur is pressed down by the hand. (b) Side view of the fur CG model stroked against the growth direction. The fur is lifted by the hand and it stands up after the hand passes.

the sensor first touches the fur. Anisotropy was observed in the haptic aspect, similar to the visual behavior. Small effects due to speed were also observed. When fur was stroked along the growth direction, steady vertical forces were observed. This trend was also observed in other directions besides the reversed direction listed in the Appendix. Conversely, when stroked in the reversed direction, a cyclic behavior similar to the visual behavior was observed. In a single cycle, forces sharply increased during the deformation phase and then gradually decreased during the rubbing phase. The behavior aligned with the results of previous studies that measured the surfaces of several upright piles [37]. Notably, our research highlights the cyclic behavior owing to long and dense fur transitioning from a flat to a flipped state. Each cycle occurred approximately every 8 cm, corresponding to the distance for a bundle of hairs, 5 cm in length and approximately 3 cm in width, collapsing and flipping.

D. Visual Model of Voluminous Fur

Various fur visual models have been proposed using CG [45], [46], [47], [48], [49]. Owing to the complexity of fur structure and the high computational costs, existing studies and common applications that enable real-time interactions with fur typically render the fur as flat textures or use static models in response to skin contact [11], [15], [16]. Interactive models typically move in response to colliding objects and are designed to gradually return to their initial angles after release. In this study, we used the Unity hair simulation system [50] to implement the phenomenon of hair standing at the end by adjusting the shape to converge based on a release point, according to the observation of visual behavior of voluminous fur in Section III-B. Fig. 3 shows the footage of manually stroking the implemented fur from two directions. When stroked forward, the fur collapsed downward and gradually returned, whereas stroking backward resulted in it standing at the end.

Our CG model achieved a frame rate of 72 frames per second on HMD (Meta Quest 3, Meta) using a laptop PC equipped with NVIDIA GeForce RTX 3080 Laptop GPU, 16 GB of system RAM, and an Intel Core i7-11800H processor.

E. Haptic Model of Voluminous Fur

To present the soft tactile sensation of voluminous fur, we selected a mid-air ultrasound tactile display capable of offering non-contact tactile stimuli, rather than rigid haptic devices. For this study, we used Ultrahaptics STRATOS Inspire equipped with 256 ultrasonic transducers and a Leap Motion Controller for hand tracking. The intensity of the mid-air ultrasound haptic feedback was adjustable from 0.0 to 1.0, with 1.0 corresponding to 10 mN on a 2.1 cm circular target. Spatiotemporal modulation (STM) [51], [52], [53] was employed to the focus point, moving it in a circle of circumference 20 cm, a common size in previous research on ultrasound haptic feedback [54], [55], [56], [57] and sufficiently small compared to the palm size of an adult male hand [58]. Regarding STM, the primary parameters comprise intensity and frequency, aside from the geometric shape. Herein, intensity refers to the magnitude of the applied force, and frequency refers to the speed at which the focal point moves along a circle.

First, we discuss the intensity design of the ultrasound haptic feedback based on the measurement results presented in Section III-C. This study primarily focuses on presenting the tactile sensation of voluminous fur, aiming to capture general characteristics rather than detailed parameter features from measurements of a single set of fur. When stroking the fur along the growth direction, the vertical reactive force $F_g(x)$ remained constant, as shown in Fig. 2, set at 0.6 for the intensity of ultrasound haptic feedback.

$$F_g(x) = F_0, \tag{1}$$

where F_0 is a constant.

In contrast, the reactive normal force exhibited a cyclic behavior when the fur was stroked against the growth direction. The behavior is illustrated in Fig. 4. The hand lifted, inverted, and released the hair bundles. Assuming hair length as l, width of the hair bundle as b, and hand height as h, the hair length when hair fell at the hand height was approximated by $\sqrt{l^2 - h^2}$. The vertical reaction force F_r during stroking in the reverse direction was considered a periodic function of $\sqrt{l^2 - h^2} + b$.

$$F_r(x) = F_r(x + \sqrt{l^2 - h^2} + b). \tag{2}$$

Within period ($0 \leq x \leq \sqrt{l^2 - h^2} + b$), the angle θ at which the hair came in contact with the skin changed linearly with x from 0 to $\frac{\pi}{2}$. Once it reached $\frac{\pi}{2}$, the angle was maintained during rubbing. Under this assumption, an existing formula for a single hair [34], [37] was extended to a bundle of hair, considering k

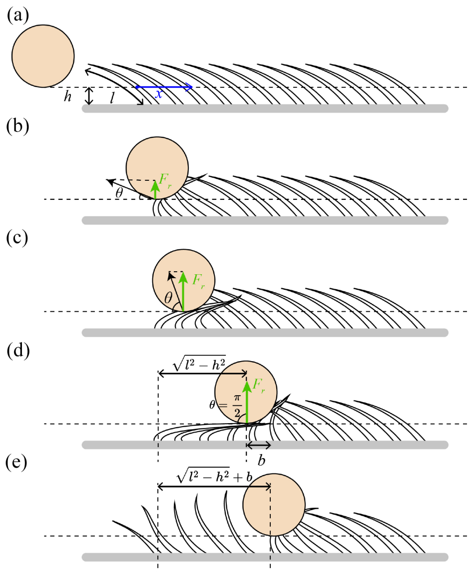

Fig. 4. Schematic depicting fur behavior when stroked against the fur growth direction. (a) When the hand moves, (b) it first comes in contact with the initial fur bundle, (c) lifts it while entangling next bundles in the deformation phase, (d) slides across the bundle width during the rubbing phase, and (e) then releases it, showing a cyclic behavior.

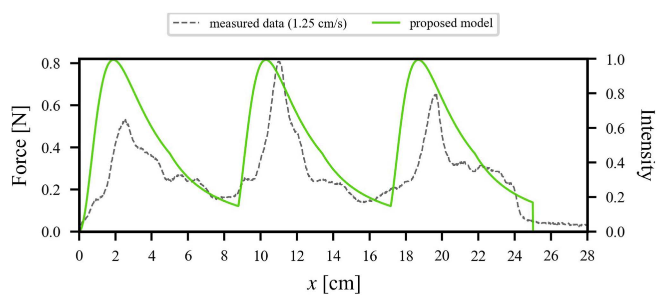

Fig. 5. Comparison of the measured force at 1.25 cm/s and the intensity of the speaker calculated by the proposed model when fur-stroking against the growth direction.

as a proportionality constant.

$$F_r(x) = k\frac{\sin^2\theta}{(h\cos\theta + x\sin\theta)^2}\ (0 \leqq x < \sqrt{l^2-h^2}+b)$$

$$\theta = \begin{cases} \frac{\pi}{2}\frac{x}{\sqrt{l^2-h^2}}\ (0 \leqq x < \sqrt{l^2-h^2}) \\ \frac{\pi}{2}\ (\sqrt{l^2-h^2} \leqq x < \sqrt{l^2-h^2}+b) \end{cases} \quad (3)$$

Fig. 5 shows the plots of the formulas along with the actual measurement results. The parameter l was set to 5.0 cm based on the hair length of the fur sample, and h was fixed to 1.0 cm according to the measurement system settings. The width of the hair bundle, b, was fitted from the cycle width of the measured data and was determined to be 3.4 cm. The proposed model captured cycles that contained a pronounced initial increase and a subsequent gradual decrease in the deformation and rubbing phase, respectively, reflecting the measured behavior.

Next, we discuss the frequency design. Existing studies have indicated that frequency alteration of the circular motion in STM influences roughness perception [54]. To the best of our knowledge, previous studies have primarily focused on subjective evaluations of perception change. Thus, roughness perception varies within a frequency range of approximately 30 Hz to 70 Hz for a circular path of 20 cm. Therefore, to simulate a smooth tactile sensation while stroking in the fur growth direction, we employed a frequency of 70 Hz. Conversely, a frequency of 30 Hz was used to evoke a rough tactile sensation when stroking against the fur growth direction.

IV. Experiment 1: Haptics

This study aims to investigate the contribution of visuo-haptic stimuli based on an interactive model of hand movements to the experience of stroking voluminous fur in VR. When attempting to recreate the sensation of fur stroking, experimental biases including the visual aspects of fur and experimental intentions can influence the results. Therefore, Experiment 1 was focused solely on haptic stimuli, where we examined the generation of fur sensation by our proposed haptic model of intensity and frequency providing further information. In Experiment 2, we assessed the closeness with which the proposed visuo-haptic model replicated the experience of stroking fur compared to real fur by incorporating a visual CG model. The Research Ethics Committee of the University of Tokyo approved the experiments presented in this and next sections (No. 23-559).

A. Participants

Eighteen participants (nine males and nine females) aged between 22 and 42 years, with an average age of 26.1, participated in this study. Among them, seventeen participants were right-handed, and three had prior exposure to ultrasound haptic feedback. The participants were recruited under the pretext of examining mid-air ultrasound haptic feedback and tactile perception without any specific mention of fur. After the experiment, the participants were informed that the study focused on fur texture perception.

B. Experimental Design

An experiment was conducted to investigate the extent to which our proposed haptic model for intensity and frequency induced fur sensations without any prior expectations of fur texture. The experiment was framed as a survey of general tactile perception using mid-air ultrasound haptic feedback. The participants were debriefed after the experiment, clarifying that the study aimed to explore the sensations of fur.

1) Experimental Conditions: The conditions of Experiment 1 were designed in combination with two levels for each factor of intensity and frequency of the mid-air ultrasound haptic feedback, resulting in a total of four conditions (Fig. 6). Both factors exhibited two levels: a static condition and an interactive condition. Under the static condition for intensity factor, the intensity was fixed at 0.6, whereas the intensity under the interactive condition was set using the formula established in Section III-E. Under the static frequency condition, the frequency was set at 50 Hz. Under the interactive condition, the frequency was set at

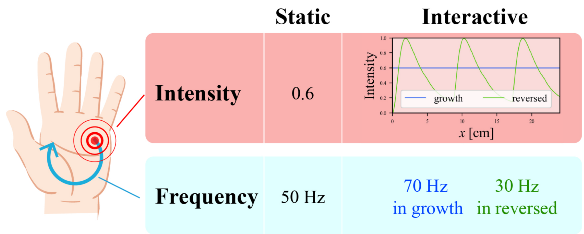

Fig. 6. Summary of experimental conditions for two factors (intensity and frequency) and two levels (static and interactive).

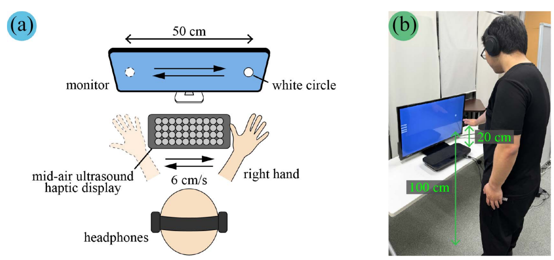

Fig. 7. (a) Schematic representation of the setup for Experiment 1. (b) Environment of a participant engaged in Experiment 1.

70 Hz in the growth direction and 30 Hz in the reverse direction. An intensity of 0.6 under the static condition was equivalent to the intensity in the growth direction under the interactive condition. The frequency of 50 Hz set in the static condition for the frequency factor was an intermediate value used in previous studies on the roughness of ultrasound feedback [54], [55] and has been utilized in several previous research [57], [59]. Within the frequency range of this experiment, no significant influence of frequency on the just noticeable difference (JND) of intensity was observed [55].

2) Experimental Setup and System: Fig. 7 illustrates the setup and the system of the experiment. For this experiment, a mid-air ultrasound haptic display, a monitor, a desk, and noise-canceling headphones (WH-1000XM4, SONY) were prepared. Haptic stimuli corresponding to the experimental condition were introduced as participants moved their right hand from right to left and from left to right. They were asked to choose one sensation that they felt was the closest among the twelve options. Twelve options included six soft materials (“Steam,” “Water,” “Gel,” “Cloth,” “Skin,” and “Fur”) and five hard materials (“Cork,” “Ice,” “Wood,” “Brick,” and “Metal”), along with an “Others (Free Answer)” option. These options other than “Fur” and “Others (Free Answer)” were selected based on specific criteria. First, to ensure the validity of the experiment in estimating tactile sensations through mid-air ultrasound haptic feedback, all options were selected from materials presented in previous studies and applications utilizing ultrasound haptic stimulation [30], [31], [32], [60], [61], [62], [63], [64], [65]. Additionally, a balanced range of options, some softer and some harder than fur, was included to avoid a bias toward the sensation of “Fur”. This experimental concept was based on the experimental designs used in previous studies [66], [67].

The hand movements of the participants were regulated by aligning them with moving markers displayed on a monitor. The method served two purposes: to ensure consistency in the stimuli presented among participants and to regulate biases in tactile perception during haptic exploration under different experimental conditions [68]. The right hand was positioned at a height of 100 cm from the floor and 20 cm from the mid-air ultrasound haptic display. The participants moved their right hand laterally over a distance of 50 cm at a speed of 6 cm/s. These values were determined by considering the operational range of the mid-air ultrasound haptic display and natural human movements without causing discomfort.

We conducted five trials for each condition, a total of 20 trials. The order of the 12 options was randomized for each trial, and the order of 20 trials was counterbalanced for each participant using a balanced Latin square [69].

C. Experimental Procedure

The participants received a deceptive experimental explanation and answered a pre-experiment questionnaire. Subsequently, the participants wore noise-cancelation headphones and stood in a designated position in front of a mid-air ultrasound haptic display. The experimental room was quiet. As white noise increases the perceived roughness of the ultrasound haptic feedback [59], no white noise was emitted from the headphones, activating only noise cancelation. Since active noise cancellation often interfere with ultrasound noise, we confirmed in advance that the active noise cancellation of the headphones and the ultrasound stimulation would function properly together.

Each trial in Experiment 1 was conducted as follows. The participants extended their right hand horizontally, guided by the position of a white circle on the monitor. After a short pause, they moved their right hand 50 cm from right to left at 6 cm/s to match the movement of the moving white circle, stopping their hand at the position where the white circle stopped. After a 3-s pause, participants moved their right hands 50 cm from left to right at 6 cm/s to match the movement of the white circle, stopping their hand at the same position as the circle. Participants were instructed to focus on their right hand during this process. After stopping their hands, participants answered a questionnaire on an iPad.

The procedure was repeated 20 times, with a 10-s break between trials. After completing all trials, the participants answered a post-experiment questionnaire. Thereafter, debriefing was conducted explaining that the main objective of the experiment was to feel the tactile sensation of fur. The duration of Experiment 1 was approximately 30 min.

D. Result

Fig. 8 shows the percentage of responses for each experimental condition across all trials. The response rate for fur was positioned on the far left side, with the remaining options shown in descending order. The results of statistical analyses are discussed further. In this study, the critical p-value was set to 0.05 ($* : p < 0.05, ** : p < 0.01$).

We first conducted the Shapiro–Wilk test to confirm data normality under each condition. Significant differences from the normal distribution were observed under all conditions.

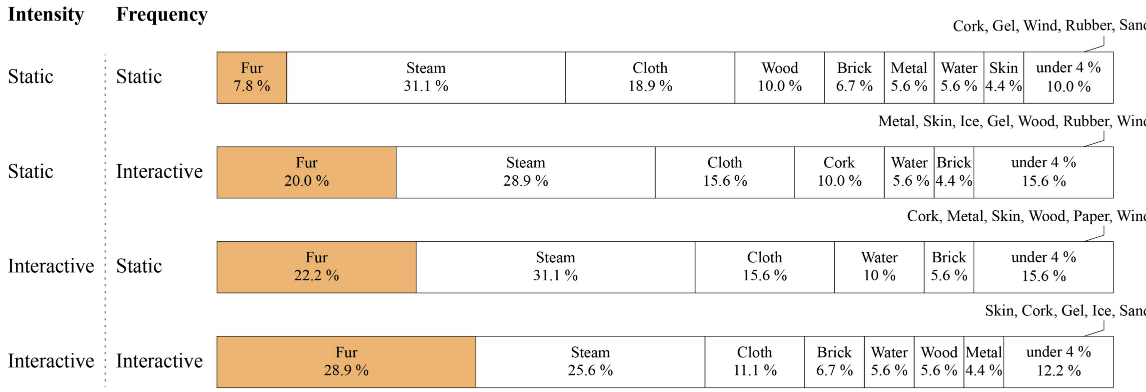

Fig. 8. Results of the percentage of responses for the perceived closest material under four conditions of ultrasound haptic feedback. "Fur," the main target of this research, is highlighted in brown, and those with a response rate of 4 % or less are summarized as "under 4 %.".

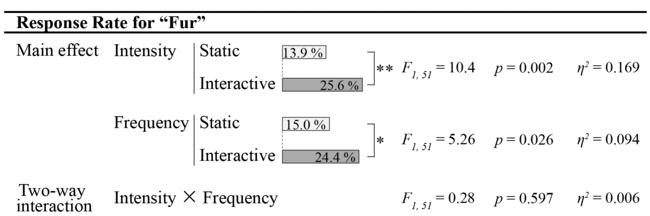

Fig. 9. Results of the two-way ART ANOVA tests for response rate for fur. Bar graphs indicate the mean values of the conditions. $*: p < 0.05$, $**: p < 0.01$.

Therefore, we performed an aligned rank transform (ART) [70] to enable us to conduct an ANOVA for non-parametric data. Hence, we conducted a two-way ANOVA. Fig. 9 summarizes the statistical test results. The results exhibited significant main effects of intensity ($F(1, 51) = 10.4$, $p = 0.002$, $\eta^2 = 0.169$) and frequency ($F(1, 51) = 5.26$, $p = 0.026$, $\eta^2 = 0.094$). The interaction effect of intensity and frequency factors was not significant ($F(1, 51) = 0.284$, $p = 0.597$, $\eta^2 = 0.006$).

Additionally, to evaluate the highest response rate of 28.9 % obtained when both factors were interactive, a binomial test was conducted to compare this rate with the chance level (16.7 %) across six materials as soft as or softer than skin ("Steam," "Water," "Gel," "Cloth," "Skin," and "Fur"). The result indicated a statistically significant difference ($p = 0.004$).

E. Discussion

First, we discuss the tactile sensation of "fur", which was the main target of Experiment 1. Statistical tests revealed significant main effects of intensity and frequency on the response rate for fur. It can thus be suggested that the proposed interactive design for the intensity and frequency of the ultrasound haptic feedback is effective in inducing the tactile sensation of fur. When both intensity and frequency of the ultrasound haptic feedback were set interactively, the highest response rate of 28.9 % was achieved under all experimental conditions; this value was also the largest among the response options for tactile sensations. A binomial test showed that 28.9 % response rate was significantly higher than the chance level among soft materials. While this value indicates that the interactive model for frequency and intensity does not fully replicate the tactile sensation of fur, it can still evoke a fur-like sensation even in the absence of prior information or visual cues related to fur.

Previous studies have explored various tactile sensations using ultrasound feedback. Although this study focuses mainly on the tactile sensation of fur, the results offer valuable insights into how ultrasound haptic stimulation is typically perceived. Across all the trials, the most frequently reported sensations were steam (29.2 %), fur (19.7 %), and cloth (15.3 %). The trend is likely due to mid-air ultrasound haptic feedback, which is a gaseous medium, being better suited for simulating soft materials. Particularly, "steam" was the only gas among the options and had the closest properties to the medium, which explains its highest response rate. Post-experiment comments by participants included, "I did not feel like I was touching a solid object" and "I consistently felt a soft stimulus." These findings provide valuable knowledge for future research and applications involving texture presentation using mid-air ultrasound haptic feedback.

V. Experiment 2: Visual and Haptic

For this study, we introduced a model for interactive visuo-haptic stimulation aimed at dynamically adjusting hand movements to simulate the tactile sensation of stroking voluminous fur. Experiment 2 was performed to assess the impact of interactive visuo-haptic models on the fur-stroking experience. In the experiment, we compared our proposed model with real fur to assess the realism of it simulating the experience of stroking voluminous fur.

A. Participants

Twenty-one participants (13 males and 8 females) aged between 22 and 47 years, with an average age of 26.9, participated in the experiment. Among them, 19 were right-handed. Three had prior exposure to ultrasonic vibrators and 18 had prior VR experience. The sample size was calculated to satisfy a significance level of 0.05, effect size of 0.5, and power of 0.6.

B. Experimental Design

The experimental conditions for Experiment 2 were a combination of two levels for each factor of the visual CG model (*Visual*) and the haptic model (*Haptic*) of the mid-air ultrasound haptic feedback, resulting in a total of four conditions. Both factors exhibited two levels: a static model (*static condition*) and an interactive model (*interactive condition*).

Under the static condition of the visual factor, the fur CG model remained undeformed on contact with the hand, while under the dynamic condition, as described in Section III-B, the fur CG model underwent deformation by the hand. This static condition represents a standard CG rendering approach commonly employed in existing studies and applications [11], [15], [16]. By establishing this condition as a baseline, we can assess the effectiveness of the proposed real-time model relative to conventional fur visual experiences. Under the static condition of the haptic factor, the intensity and frequency of the ultrasound haptic feedback remained static with hand movement, consistent with the *Intensity-Static & Frequency-Static* condition in Experiment 1. Under the dynamic condition of the haptic factor, the intensity and frequency of the ultrasound haptic feedback varied with the hand movement based on the proposed haptic model, mirroring the *Intensity-Interactive & Frequency-Interactive* condition in Experiment 1, with h fixed at 1.0 cm.

To establish a basis for assessing the tactile experience of stroking fur, participants were instructed to stroke real fur horizontally before receiving visuo-tactile stimulation in each trial. The real fur used was the same as that used in Section III-A, and the position of the fur was set at the same height as the position for presenting the ultrasound haptic feedback to align with the posture and hand movements during the stimuli. Following real fur stroking, the participants were exposed to visuo-tactile stimuli based on the experimental conditions. Subsequently, they completed a questionnaire assessing their perception of the presented stimuli. Each evaluation item was scored on a 10-point scale and encompassed the reality of the fur-stroking experience (1: does not feel like stroking fur at all; 10: fully feels like stroking fur), perceived softness (1: not soft at all; 10: fully soft), comfort of the fur (1: not comfortable at all; 10: fully comfortable), and enjoyment during the trial (1: did not enjoy at all; 10: fully enjoyed). The questionnaire was completed using an iPad.

We conducted one trial for each condition, with a total of four trials. The order of the four trials was counterbalanced for each participant using a balanced Latin square [69].

C. Procedure

The participants received an explanation of the experiment and they provided written informed consent. Each trial was performed in accordance with the experimental conditions. The flow of each trial is illustrated in Fig. 10.

The contents of each trial included: first, the participants stood in front of a real fur placed on a 100 cm-high stand. Then, they stroked the fur from left to right and from right to left, aligning it with a moving white circle on the monitor, replicating Experiment 1. Following the stroke, they stood in front of the ultrasound transducer array wearing an HMD (Meta Quest 3, Meta) and noise-cancelation headphones (WH-1000XM4, SONY). The participants placed their hands to the right of the fur using the position of a white guide ball on the VR space and moved their hands from right to left in the natural direction of fur growth, synchronizing with the ball movement. After reaching the left end, they stopped for 3 s and then moved their hands from left to right in the reverse direction, mirroring the motion of stroking fur. Subsequently, they removed the HMD and headphones. Then, they completed a questionnaire on an iPad. A 1-min break was given between each trial. After completing all trials, the participants completed a post-experiment questionnaire. The duration of Experiment 2 was 30 min.

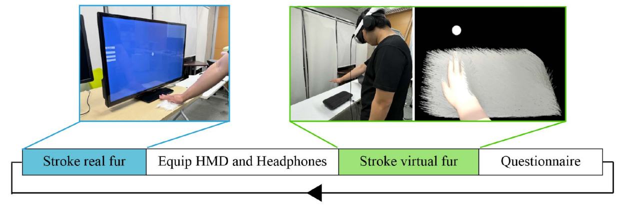

Fig. 10. Flow of each trial in Experiment 2.

D. Result

Fig. 11 shows a box plot of the 10-point scale scores for fur sensations, softness, comfort, and enjoyment. We performed ART [70] and conducted a two-way ANOVA. Fig. 12 summarizes the statistical test results.

1) Fur Sensation: For fur sensation, the results showed a significant main effect of visual factor ($F(1, 60) = 58.1$, $p < 0.001$, $\eta^2 = 0.492$) and significant main effect of haptic factor ($F(1, 60) = 12.6$, $p < 0.001$, $\eta^2 = 0.174$). The interaction effect of visual and haptic factors was not significant ($F(1, 60) = 1.06$, $p = 0.307$, $\eta^2 = 0.017$).

2) Softness: Regarding the perception of softness, the results showed a significant main effect of visual factors on fur sensation ($F(1, 60) = 13.3$, $p < 0.001$, $\eta^2 = 0.181$) and a significant main effect of haptic factor ($F(1, 60) = 5.87$, $p = 0.018$, $\eta^2 = 0.089$). The interaction effect of visual and haptic factors was not significant ($F(1, 60) = 0.209$, $p = 0.649$, $\eta^2 = 0.003$).

3) Comfort: For the sensation of comfort, the results showed a significant main effect of visual factors on fur sensation ($F(1, 60) = 18.2$, $p < 0.001$, $\eta^2 = 0.233$) and no significant main effect of haptic factor ($F(1, 60) = 1.50$, $p = 0.226$, $\eta^2 = 0.024$). The interaction effect of visual and haptic factors was not significant ($F(1, 60) = 0.180$, $p = 0.673$, $\eta^2 = 0.003$).

Previous studies have suggested an association between softness and comfort [71], [72], [73]. Therefore, to assess the relationship between the perception of softness and comfort, Spearman's rank-order correlation was conducted. The analysis revealed a strong positive correlation between the two variables, $r_s = 0.86$, which was statistically significant ($p < 0.001$).

4) Enjoyment: For the sensation of enjoyment, the results showed a significant main effect of visual factors on fur sensation ($F(1, 60) = 15.5$, $p < 0.001$, $\eta^2 = 0.206$) and no significant

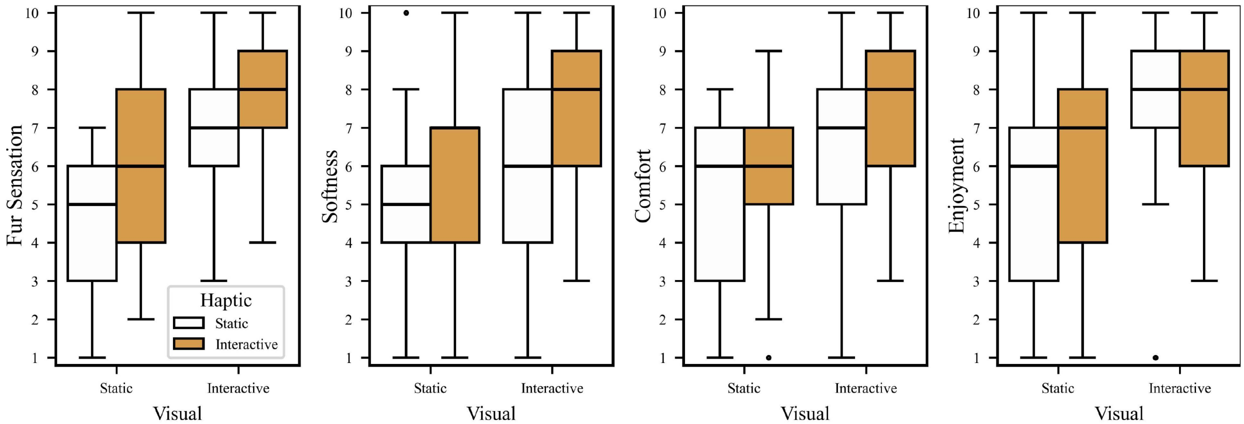

Fig. 11. Box plot of "Fur Sensation," "Softness," "Comfort," and "Enjoyment." Data points that are away from the median by more than 1.5 times the interquartile range are denoted as outliers.

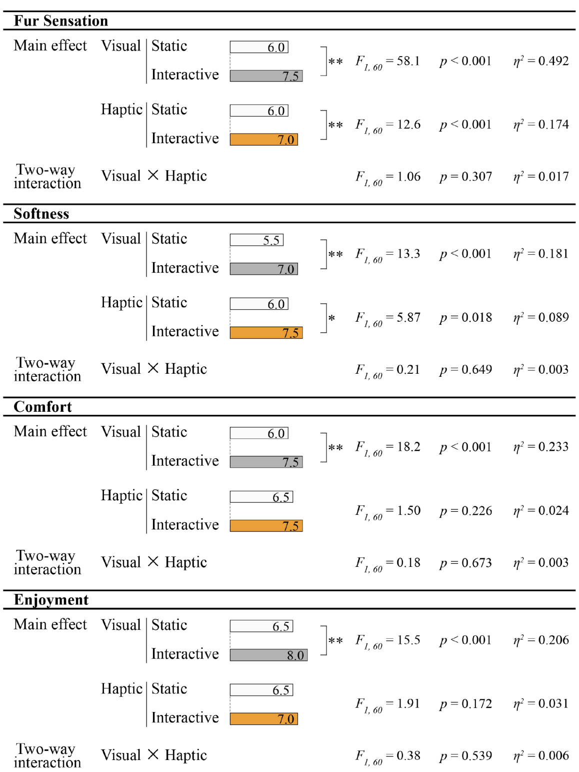

Fig. 12. Results of the two-way ART and ANOVA tests for "Fur sensation," "Softness," "Comfort," and "Enjoyment." Bar graphs indicate the median values of the conditions $*: p < 0.05$, $**: p < 0.01$.

main effect of haptic factor ($F(1, 60) = 1.91$, $p = 0.172$, $\eta^2 = 0.031$). The interaction effect of visual and haptic factors was not significant ($F(1, 60) = 0.382$, $p = 0.539$, $\eta^2 = 0.006$).

E. Discussion

Considering the fur sensation, significant main effects were observed for both visual and haptic factors. Thus, the proposed interactive design is effective in enhancing the reality of voluminous fur experience in terms of both visual and haptic aspects, even when compared to actual voluminous fur. The significant enhancement of the fur sensation by interactive haptic design can be interpreted as successfully achieving the presentation of fur volume by displaying differences in the bending of the fur and the corresponding variations in reactive force and roughness based on the direction of stroking. These findings were also supported by the enhancement in the perception of softness, which will be discussed later. The highest median at 8.0 and mean values at 7.8 were obtained when both factors interacted. In the post-experiment questionnaire, participants reported this condition with comments, "The alignment of visual and haptic stimuli made the fur sensation more pronounced" and "The tactile sensation of fur in VR was very close to that of real fur." These comments indicate that, while the detailed parameters of the fur texture were not yet precisely rendered, the stroking experience of voluminous fur was realistically conveyed.

However, two main points of free responses regarding the differences compared to actual fur were reported. The first concerned the base of the fur or the skin. Although the measurements and model generation in this study accounted for the reaction force from the skin beneath the fur, there remained a noticeable difference in the sense of solid resistance when comparing the reference task of stroking real fur with the VR task of stroking virtual fur. In the reference task, the hand was supported by both the fur and the underlying table, whereas in the VR experience, participants needed to maintain the height of their hand themselves. This difference is due to a fundamental limitation: mid-air ultrasound haptic stimulation, being non-contact and relatively weak, cannot physically support or manipulate the hand. This limitation was noted in comments, such as "In VR, it felt like passing my hand through a bundle of ostrich feathers" and "Combining visual and tactile sensations made it feel surprisingly fur-like. The overall fluffy sensation and smooth tips were noticeable, but the absence of a solid feeling in the underlying skin made it less realistic." The second point concerned thermal sensation. Previous studies have used ultrasonic stimulation and mist to present cold sensations [32], [74], [75]; however, our study only presented tactile feedback and we did not present the actual coolness of fur.

Regarding the perception of fur softness, significant effects were observed for both visual and haptic factors. Thus, visual deformation and haptic changes both enhance the perception of fur softness. The obtained results for softness agreed with the findings of previous studies, where displacement, force distribution, and contact area when pressing an object influenced the perception of softness [76], [77], [78], [79]. Focusing on haptic modality, our study dynamically changed the reactive force in response to hand movements without changing the spatial distribution of haptic stimuli. Increasing the intensity of the ultrasound haptic feedback in response to displacement during reversed stroking can contribute to softness perception, similar to that of a spring model [64].

Significant main effects on comfort and enjoyment were observed for visual factors but not for haptic factors. Further statistical tests revealed a strong positive correlation between the perceptions of softness and comfort. The finding was consistent with those of previous studies on the relationship between softness and comfort [71], [73]. While the interactive design of haptic stimuli contributed to comfort from the perspective of softness, the prickly sensation caused by air bubbles in the ultrasound feedback likely had a negative impact on comfort and enjoyment during fur interaction. In the post-experiment questionnaire, a comment read, “Ultrasound stimulation was more tingling than the actual tactile sensation of the fur.” Recent studies have indicated that multi-point STM can deliver a mild tactile sensation suitable for relaxation [57]. For applications focusing on comfort, the proposed model requires an adjustment in the number of focal points. Another factor that may have contributed to the limited improvement in comfort and enjoyment is the content of the experience itself. Since the primary focus of this study was on evoking the sensation of fur texture, the interaction was limited to simply stroking a fur-like surface, which may be felt monotonous or unengaging. Incorporating content such as animals or virtual creatures aimed at enhancing comfort and enjoyment could potentially yield better results.

VI. Limitation and Future Work

This study is the first to investigate the simulated presentation of voluminous fur by focusing on the induction of fur sensation. Our study had several limitations. First, regarding hand movements, our study limited hand interactions to stroking in the primary two directions, which is considered the most common interaction with fur. However, interactions with voluminous fur can involve various hand movements, such as pinching or pressing vertically. The position of the haptic stimulation is also a limitation. Our study used only the normal force with a circular STM on the palm, which is a basic method for presenting ultrasound haptic feedback. However, interactions with fur also involve shear forces and spatial elements such as the spaces between fingers or sides of the hand. These missing components may be essential for enhancing the realism of fur interactions and for representing a broader variety of fur textures. Third, concerning the type of fur used, our experiments set the parameters for visual and haptic modalities based on a simple voluminous fur sample. Although our method is effective for soft fur, presenting the tactile sensation of brush-like stiff hair is difficult owing to the output limitation of ultrasonic transducers. By adjusting the parameters of the proposed model, we can achieve the experience of stroking soft fur that covers the entire palm. However, other types of fur interactions require modifications to the model.

Updating the model to address these limitations can enable more realistic and diverse fur interactions in future studies. We believe that, in addition to the measurements of various directions provided in the Appendix, conducting measurements and simulations with various fur samples and interaction methods will make it possible to update these models. Furthermore, verifying the effectiveness of presenting various tactile fur sensations in animal-assisted therapy, entertainment, and online shopping applications is crucial.

VII. Conclusion

This paper presents a novel approach for simulating the experience of stroking voluminous fur using an interactive visuo-haptic model in virtual reality. Based on the observations and measurements of stroking fur, we focused on the anisotropy of voluminous fur and developed interactive models for both visual and haptic modalities. By employing a mid-air ultrasound haptic feedback system and detailed CG models of fur, we achieved a realistic replication of the soft, voluminous texture of fur. Our experiments validate the effectiveness of the proposed model in evoking the sensation of voluminous fur stroking, with significant contributions from the interactive models of both visual and haptic feedback. Despite limitations such as the absence of underlying skin resistance and thermal sensations, this study is the first to introduce an interactive model for virtual fur interactions, laying the groundwork for future research aimed at achieving a more complex and versatile experience. Future research will address these current limitations and explore broader applications in therapeutic and entertainment domains.

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