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Enhancing Smoothness Perception in Mid-Air Haptic Systems: Introducing Continuity Length and Movement-Adaptive Feedback for Active Touch

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***Abstract*—Smoothness is an essential tactile characteristic for virtual texture simulation. However, research on its haptic rendering remains limited compared to the well-explored domain of roughness. Existing methods often define smoothness as simply the absence of roughness, oversimplifying its continuous nature and limiting the potential of haptic systems to fully express its quality. In this study, we introduce a novel haptic parameter, continuity length (CL), designed to render smoothness through continuous feedback. CL represents the continuous shift of the feedback point over a specified length, enabling spatial continuity and creating a seamless tactile experience. Furthermore, when feedback is applied in a fixed direction, regardless of the user's hand movements, misalignment between the hand movement and the feedback can diminish the perception of smoothness in active touch scenarios involving exploratory interaction with objects. To address this, we propose a CL-based movement-adaptive haptic rendering approach. By dynamically adjusting the feedback point in the opposite direction of the user's hand movement, this method ensures alignment between movement and feedback, preserving tactile continuity. User studies show that the CL-based adaptive rendering effectively conveys smoothness, especially for textures like cloth and fur. This approach enhances the expressive capabilities of haptic systems, enabling richer tactile experiences in virtual reality.**

***Index Terms*—Haptic Rendering, Smoothness Perception, Mid-Air Haptics**

I. Introduction

In virtual reality (VR), the rendering of haptic textures is crucial in enhancing the user experience. For example, simulating the textures of fabrics, wood, or metal surfaces allows users to feel differences in roughness, hardness, and friction, enhancing the realism of virtual interactions. Among tactile representations of textures, roughness is one of the most prominent attributes [1], and extensive research has been conducted on haptic rendering of roughness [2]–[7]. Specifically, vibration amplitude and frequency have been identified as key parameters in influencing roughness perception. Previous studies have suggested that higher amplitudes or lower frequencies are associated with an increased perception of roughness [3], [8].

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However, studies on the haptic rendering of smoothness remain relatively unexplored. Smoothness is a tactile characteristic that cannot simply be expressed as the reverse of roughness. Although roughness stimulates the tactile system through surface irregularities [9] and protrusions [10], smoothness is characterized by continuous contact and reduced friction, providing a consistent sensory experience [11], [12]. Defining smoothness by simply inverting roughness-based techniques is inadequate. Smoothness in active touch is better characterized by continuous contact, requiring both temporal and spatial continuity. While frequency may support the perception of temporal continuity and thus contribute to smoothness, it is not sufficient on its own. To fully convey smoothness, it is especially important to ensure spatial continuity. This study aims to fill this gap by introducing a novel approach to effectively render smoothness in haptic systems. Thus, we propose a new haptic parameter, **continuity length (CL)**, that enables uninterrupted feedback by shifting the feedback point over a defined length to achieve spatial continuity in tactile stimulation. Consequently, CL ensures a continuous tactile experience, making it a more suitable representation of smoothness compared to the inverse modeling of roughness-based techniques.

In the real world, smoothness perception arises through active touch and hand movements, a principle that similarly applies to texture experiences in virtual environments. Yet, when CL is applied in a fixed direction, independent of the user's hand movements, discrepancies between the feedback and the user's movement may arise, which negatively impacts the perception of smoothness.

To address this limitation, we introduce a **CL-based movement-adaptive haptic rendering** method. By dynamically shifting the feedback point in the opposite direction of the hand movement, the proposed approach ensures alignment between the user's movement and the feedback direction. This mechanism aims to maintain the continuity of the feedback, thereby enabling CL to more effectively convey smoothness in virtual interaction scenarios. To achieve this, we employed ultrasound amplitude modulation as the haptic rendering method, ensuring continuous feedback and alignment with the user's hand movement direction. User evaluations demonstrated that the CL-based movement-adaptive haptic rendering method can effectively represent smoothness during interactions with virtual environments for both cloth and fur textures, validating its effectiveness in virtual reality.

The key contributions of this study are as follows:

- We introduce a novel haptic parameter, **continuity length (CL)**, which captures spatial continuity and thus provides a more effective representation of smoothness compared to conventional haptic parameters for roughness.
- We propose a **CL-based movement-adaptive haptic rendering** method, integrating dynamic hand movement to deliver a seamless and smooth experience in active touch scenarios.
- We demonstrate the effectiveness of our CL-based movement-adaptive haptic rendering through experiments involving interactions with various virtual objects.

II. Related Works

A. Roughness perception and haptic rendering

Roughness perception is a fundamental aspect of tactile sensation, forming one of the key dimensions of tactile perception [1]. Recent studies have investigated the mechanisms of roughness perception, focusing on its relationship with physical tactile parameters. Early works by Lederman and Taylor [13] established foundational knowledge by investigating the psychophysical relationships between surface texture and perceived roughness. They identified key parameters, such as the size and spacing of surface texture elements, and demonstrated that the perception of roughness increases with the spatial frequency of surface textures up to a certain point, after which it decreases. Additionally, Tymms et al. [9] found that textures with larger spatial periods and smaller texture elements induce higher roughness ratings, emphasizing the importance of protrusion size and arrangement in roughness perception. Similarly, Sutu et al. [10] revealed that the combination of the height and spacing of texture dots has a compound effect on tactile roughness perception, further supporting the role of surface irregularities as critical factors in roughness perception. In addition to spatial properties, temporal cues have also been shown to influence roughness perception. Cascio and Sathian [14] demonstrated that spatial factors alone are insufficient, highlighting the contribution of temporal dynamics in tactile roughness. However, it is important to note that discussions of temporal factors may involve differing units or measurement criteria, which should be taken into account when interpreting or comparing results.

Vibration techniques have been widely used for haptic rendering of roughness. Consequently, significant research has focused on vibrotactile rendering of roughness with frequency and amplitude identified as the primary parameters for representing roughness. For example, Chen et al. [3] and Deng et al. [4] emphasized that higher amplitudes and lower frequencies are associated with increased roughness perception. Similar findings have been presented by other studies, such as Dobes et al. [5] and Kang et al. [6], which further solidify frequency and amplitude as dominant factors in roughness representation. Furthermore, a study in ultrasound haptics demonstrated the use of frequency modulation to represent tactile roughness [7]. Accordingly, roughness in haptic rendering can be predominantly represented by capturing surface protrusions and irregularities through vibration-based techniques, primarily by adjusting frequency and amplitude.

B. Smoothness perception and haptic rendering

While smoothness rendering is often treated as the inverse of roughness rendering, this simplistic approach fails to capture smoothness in haptic systems. Hollins et al. [8] showed that increasing the amplitude of imposed vibrations decreases the perception of smoothness. Tanaka et al. [15] found that roughness is most pronounced at 50 Hz and 200 Hz, with 200 Hz inducing a smoother sensation and 50 Hz a less smooth one due to optimal activation of Meissner and Pacinian corpuscles.

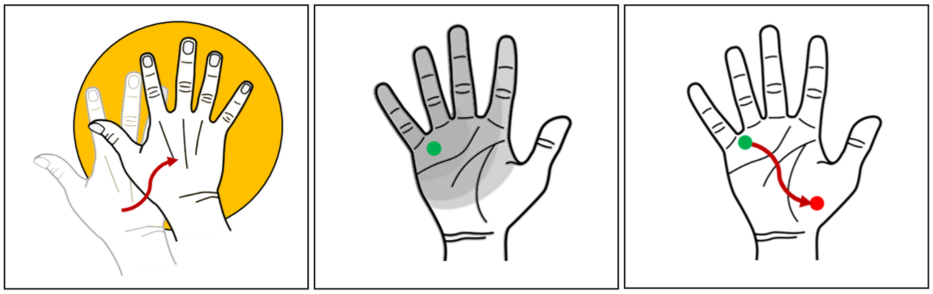
However, unlike roughness, tactile smoothness perception is primarily driven by continuous contact [11] and low friction [12]. Therefore, rather than simply inverting roughness parameters, smoothness rendering should be represented using a new parameter that aligns with the characteristics of smoothness. This gap emphasizes the need for novel strategies, such as the proposed *continuity Length* (CL), to effectively capture and convey the distinct characteristics of smoothness.

C. Hand movement based Haptic Rendering

Hand movements play a pivotal role in tactile perception. Studies on active touch have demonstrated that exploratory hand movements, such as stroking or sliding, are critical for perceiving surface properties, including texture and roughness [16]–[19]. These studies emphasize that tactile perception is not a passive process but an interactive one, where hand movement actively modulates sensory input.

Moreover, hand movement and the direction of feedback can also influence perception. Humans have a natural tendency to suppress irrelevant tactile signals while enhancing signals related to movement, which further supports the importance of aligning feedback with user movement [20]. Ryan et al. [21] showed that movement and texture cues interact to shape tactile perception, and any misalignment between movement direction and feedback signals can negatively impact the user's sensory experience. Such misalignments disrupt the continuity of tactile feedback and are particularly problematic when the feedback direction is inconsistent with the user's natural hand movements.

To address these challenges, this study introduces a movement-adaptive haptic rendering method designed to ensure seamless alignment between user movement and feedback. By dynamically adjusting the feedback point to move in the opposite direction of the user's hand movement, this method aligns movement with feedback, enhancing smoothness perception.



(a) (b) (c)

Fig. 1: **Overview of the haptic rendering process incorporating continuity length.** (a) The hand interacts with a virtual object through stroking. (b) A pressure field is generated based on the computed pressure, and local maxima points within the field are identified. (c) The movement adaptive haptic rendering process dynamically shifts the feedback point in the opposite direction to the hand movement by a specified continuity length within the palm's coordinate system.

D. Ultrasound haptic rendering

Ultrasound haptic technology utilizes acoustic radiation pressure generated by a transducer array to provide mid-air haptic feedback [22]. Its ability to freely designate feedback points enables high haptic resolution, making it well-suited for CL that requires continuous feedback. Ultrasound modulation can be divided into three methods: amplitude modulation (AM), spatiotemporal modulation (STM), and lateral modulation (LM). In AM, the intensity of a focal point—where ultrasound signals converge—varies over time. In contrast, STM applies force by shifting the location of focal points while keeping their intensity constant. Traditionally, STM applies force to a single point, but a recent development introduces multi-point STM, in which feedback is provided to multiple points simultaneously [23]. On the other hand, LM applies force by laterally shifting the position of a focal point [24]. However, STM or LM inherently involves the traversal of a focal point along a trajectory, making it unsuitable for providing unidirectional feedback. Therefore, we utilized AM to implement feedback in the opposite direction to hand movement.

Ultrasound haptics have been widely employed in simulations to mimic the tactile sensations of real objects. In virtual object interaction scenarios, one method for determining feedback points relies on the pressure field induced by collisions. When a hand interacts with a physically modeled virtual object, pressure computation is performed to estimate the collision force. During this process, the position of focal points are calculated to map the pressure field. This data is then used to generate an acoustic force applied to the physical hand, effectively simulating real-world tactile sensations. For instance, Jang and Park [25] developed a realistic fluid simulation using the Smooth Particle Hydrodynamics (SPH) approach to estimate the pressure field through local maxima searching combined with AM. Barreiro et al. [26] used AM and clustering to simulate fluid interactions, optimizing focal points to match the target pressure field. They later incorporated STM with a path routing algorithm [27]. Additionally, in clay simulations, they applied a weighted clustering algorithm to replicate tactile pressure [28].

Drawing on these advancements, we propose that our method can be applied to a wide range of virtual object interactions. Building on the method proposed by [25], we first identify local maxima and then apply our CL-based movement-adaptive approach to represent the smoothness of various virtual objects. This versatility underscores its potential to enhance diverse haptic applications, further expanding the expressive capabilities of haptic rendering.

III. Continuity Length

Continuity Length (CL) is a novel haptic parameter designed to enhance the perception of smoothness through seamless feedback. CL is defined as the maximum distance over which a feedback point moves continuously without interruption. The direction of continuous movement of the feedback point can dynamically change depending on the interaction environment or system settings. The position of feedback point at time t, denoted as $P_{feedback}(t)$, is updated as follows:

$$P_{feedback}(t + \Delta t) = P_{feedback}(t) + v(t) \cdot \Delta t, \qquad (1)$$

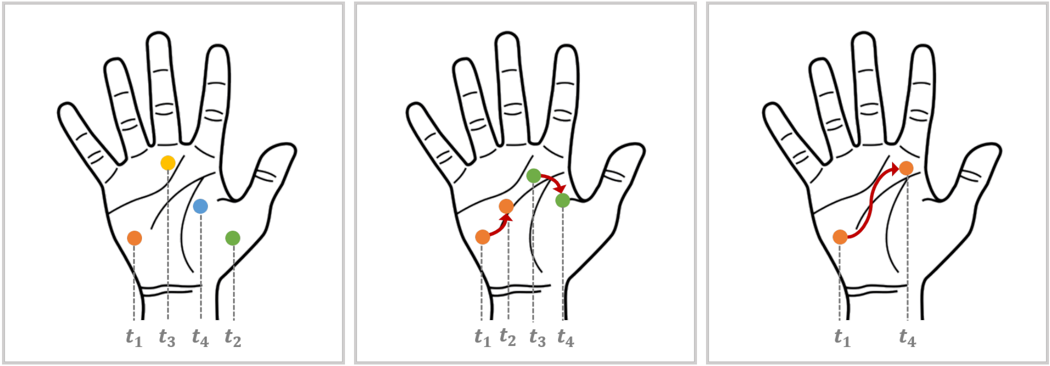
where $v(t)$ represents the velocity vector of the feedback point at time t, which is not fixed and may vary over time, and Δt is the time step for updating the position. The total movement of the feedback point is constrained by the predefined CL L, ensuring that the feedback point remains within the permitted range. The constraint for feedback distance is expressed as:

$$\int_{t_0}^{t_1} |v(t)| dt \leq L, \qquad (2)$$

where duration $[t_0, t_1]$ defines the interval during which the feedback moves continuously and L denotes the continuity length. If the total distance traveled by the feedback point reaches CL, the system resets the starting point to begin a new CL interval. This ensures a continuous tactile sensation over a defined distance, effectively capturing the seamless nature of tactile smoothness.

IV. Movement-Adaptive Haptic Rendering

Movement-adaptive haptic rendering is designed to enhance continuity and effectively convey smoothness when applying CL in scenarios where users actively move their hands to perceive the texture of virtual objects. It dynamically adjusts



(a) (b) (c)

Fig. 2: **Visualization of the feedback process in movement-adaptive haptic rendering depending on continuity length (CL).** (a) When CL is not applied, the feedback point discretely shifts by identifying a new local maximum at each timestep. (b) When CL is shorter than the hand's movement distance, the feedback point shifts by the CL length from t_1 to t_2, after which a new local maximum is identified at t_3 and set as the starting point for subsequent feedback adjustments. The feedback then moves again for the defined CL until t_4. (c) When CL is longer than the hand's movement distance, the feedback point moves continuously in the opposite direction to the hand's movement without interruption from t_1 to t_4.

the feedback point by shifting it in the opposite direction of the hand movement accounting for the interaction speed within the palm coordinate system, preventing misalignment between hand movement and haptic feedback.

The overall haptic rendering process is outlined in Fig. 1. We first apply an existing method [25] to select the initial points where continuous movement begins. The virtual object is physically simulated using a particle-based model, while the hand surface is represented as a real-time point cloud. When the particles from the hand and the virtual object collide in the simulation, the resulting interaction forces and the total force of the surrounding particles are computed. Based on these forces, a pressure field is generated by calculating the pressure resulting from the collision between the hand and the virtual object. After the pressure field is constructed, the local maximum within the field is identified. This point corresponds to the region where the interaction force is strongest, intuitively representing the most prominent area of contact between the surface of the hand and the virtual object. This local maximum serves as the initial position for the continuous movement of the feedback point. Then the position update in Eq. 1 can be modified as:

$$P_{feedback}(t + \Delta t) = P_{feedback}(t) - \hat{v}_{hand}(t) \cdot \Delta t, \qquad (3)$$

where $\hat{v}_{hand}(t)$ is the hand movement's velocity, and Δt is the time step. This ensures that the feedback point moves in the opposite direction to the hand movement based on the palm coordinate system, maintaining its continuity. The total distance traveled by the feedback point is constrained by a predefined continuity length L:

$$\int_{t_0}^{t_1} |\hat{v}_{hand}(t)| dt \leq L. \qquad (4)$$

When the cumulative distance reaches CL, the feedback point jumps to the local maximum recalculated at that moment. From this newly identified position, the system continues to provide continuous feedback by dynamically adjusting the feedback point based on the user's hand movement, repeating the process for continuity length L.

The feedback process for movement-adaptive haptic rendering depending on CL is visualized in Fig. 2. When CL is not applied, the feedback point shifts discretely by identifying a new local maximum at each timestep, as shown in Fig. 2a. If the CL is shorter than the distance of the hand's movement, a new local maximum is searched for once the feedback point has moved by CL as shown in Fig. 2b, which is then set as the initial point for subsequent feedback adjustment based on the hand's movement. Conversely, if the CL is longer than the hand's movement distance, the feedback point moves continuously in the opposite direction to the hand's movement without interruption as shown in Fig. 2c.

In developing this movement-adaptive approach, we utilize ultrasound amplitude modulation. This approach leverages the high haptic resolution of ultrasound devices, enabling the delivery of continuous feedback critical for representing CL. Moreover, amplitude modulation ensures that feedback aligns with the user's hand movement, as it avoids the need for traversing focal points, a limitation often encountered in other modulation techniques.

V. Preliminary Study

To investigate the effective expression of smoothness in virtual object interactions, we formulate three key research questions. These questions aim to explore the role of continuity length (CL) and movement-adaptive haptic rendering in enhancing the perception of smoothness, as well as their applicability toward various virtual objects. Specifically, we examine (1) the relative influence of CL in comparison to conventional roughness-related haptic parameters, (2) the effectiveness of movement-adaptive haptic feedback in providing seamless and smooth haptic experiences, and (3) the feasibility of applying CL-based movement-adaptive haptic rendering across diverse virtual interactions. The following research questions guide our investigation:

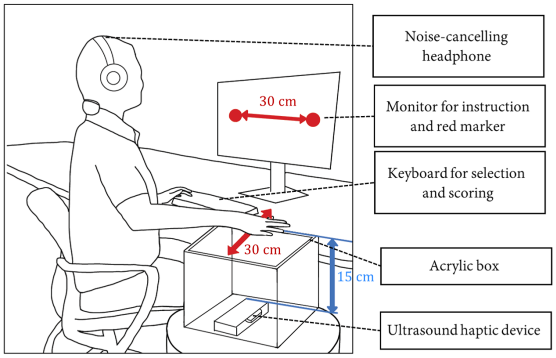


Fig. 3: **Experiment settings for preliminary study.** A sketch demonstrating the real-world setup for participants during the preliminary experiments.

RQ1. Does continuity length (CL) have a stronger impact on smoothness perception than existing haptic parameters for roughness?
RQ2. Does movement-adaptive haptic rendering enhance the continuity and smoothness of the tactile experience compared to fixed-direction feedback?
RQ3. Can CL-based movement-adaptive haptic rendering be effectively applied to various virtual object interactions?

For the first research question, we aim to determine whether CL has a greater impact on the perception of smoothness compared to intensity and frequency. To ensure a fair comparison, it is crucial to first establish the optimal values of each haptic parameter for smoothness perception. Therefore, we conducted preliminary studies specifically designed to address the first research question.

In the first phase of the preliminary study, we identified potential CL values that produce a significant difference in smoothness perception. In the second phase, we determined intensity levels that yield a meaningful smoothness difference. In our study, intensity is defined on a 0–100% scale, where 100% intensity represents the maximum amplitude that the ultrasound haptic device can output. In the third phase, we calibrated the output intensity across different frequencies to eliminate the effect of frequency-dependent perceived intensity on smoothness perception. Specifically, we selected two frequency values, 50Hz and 200Hz, following the previous work that has analyzed the effect of frequencies on smoothness perception [15]. However, it has been confirmed that 50 Hz has a lower perceived intensity compared to 200 Hz [29]. As a result, despite the fact that 50 Hz should inherently be perceived as significantly less smooth than 200 Hz, its lower perceived intensity may unexpectedly make it feel smoother. To address this issue, we calibrated the output intensity of 200 Hz to match the perceived intensity of 50 Hz at 100% output intensity in the third experiment of the preliminary study. This allowed us to assess the impact of frequency on smoothness perception more accurately.

A. Participants

For the preliminary study, we recruited 32 participants aged between 20 and 33 years (23 males, 9 females; mean age: 23.78 years, standard deviation: 3.25). Among them, 4 participants had used the Ultraleap device 1–2 times, while the remaining participants had no prior experience. There were 30 right-handed participants and 2 left-handed participants, and none of them had any skin conditions on their palms. We note that all procedures were conducted after obtaining official approval from the Institutional Review Board (IRB) of KAIST (IRB approval no. KH2024-184) and informed consent from the participants.

TABLE I
BONFERRONI-CORRECTED PAIRED T-TEST P-VALUES FOR SMOOTHNESS SCORES ACROSS CL PAIRS.

CL	1 cm	2 cm	3 cm	4 cm	5 cm
0 cm	1.000	1.000	1.000	**1.2e-3**	**3.0e-4**
1 cm	-	1.000	1.000	**0.012**	**0.008**
2 cm	-	-	1.000	**0.019**	**0.009**
3 cm	-	-	-	**0.024**	**0.003**
4 cm	-	-	-	-	1.000

*Significant values ($p < 0.05$) are highlighted in **bold**.

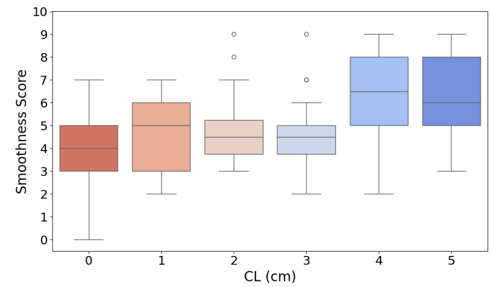


Fig. 4: **Box plot of smoothness scores for continuity length (CL) values.** Smoothness scores for CL of 4 cm and 5 cm are significantly higher compared to those for 0 cm, 1 cm, 2 cm, and 3 cm.

B. Experimental Setup

The experimental setup is illustrated in Fig. 3. In all of the experiments, we utilized the Ultraleap haptics array (HDK-REC192) for tactile feedback and Leap Motion 2 for hand tracking. The ultrasound haptic device was positioned beneath the participant's right hand, with an open-top acrylic box serving as a location guide to ensure consistent hand placement. This setup allows haptic feedback to be delivered to the palm as participants move their hands horizontally over a 15 cm distance, maintaining an optimal height based on the Ultraleap datasheet. In all preliminary experiments, a virtual sphere with a 30 cm diameter was used as the haptic target. Its curved and voluminous surface provided a more natural and evenly distributed pressure field than that of a flat surface or other curved shapes, making it suitable for evaluating smoothness perception. To eliminate auditory distractions from the haptic device, participants wore noise-canceling headphones playing white noise. Instructions were displayed on a monitor and participants interacted with the experiment by following on-screen prompts, making selections, and entering responses via a keyboard. To ensure a consistent speed and trajectory in the active touch condition, participants followed a red marker on the screen that oscillates twice at a speed of 10

TABLE II

BONFERRONI-CORRECTED PAIRED T-TEST P-VALUES FOR INTENSITY-LEVEL SMOOTHNESS COMPARISONS WITHOUT CONTINUITY LENGTH (CL).

Intensity	60%	70%	80%	90%	100%
50%	1.000	1.000	**1.0e-4**	**3.4e-7**	**7.4e-7**
60%	-	1.000	**5.7e-6**	**1.2e-8**	**5.1e-8**
70%	-	-	**1.2e-3**	**1.6e-6**	**5.0e-6**
80%	-	-	-	0.393	0.370
90%	-	-	-	-	1.000

*Significant values ($p < 0.05$) are highlighted in **bold**.

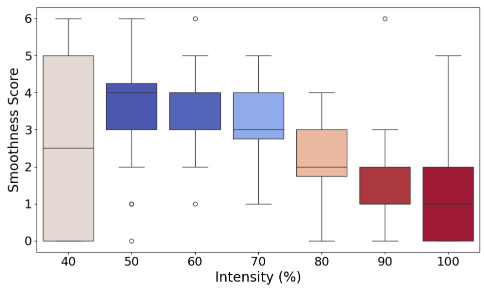


Fig. 5: **Box plots of smoothness scores for intensity values without continuity length (CL).** All feedback stimuli were delivered at a constant frequency of 200 Hz.

The intensity of 40% is excluded from the analysis because of its large standard deviation. Smoothness scores for intensities of 50%, 60%, and 70% are significantly higher than those for 80%, 90%, and 100%.

cm/s over a distance of 30 cm. This procedure was applied consistently across all experiments of the preliminary study. In addition, the number of focal points where ultrasound waves are concentrated was one.

C. Experiment 1: Finding Optimal CL values for Smoothness Perception

1) Process: In this experiment, we aim to identify CL values that result in a noticeable difference in smoothness perception. We employed a Two-Alternative Forced Choice (2-AFC) method to assess smoothness perception. Participants were sequentially presented with haptic feedback for two different CL values and were then asked to select which feedback feels smoother: the first or the second. The CL values, ranging from 0 cm to 5 cm in 1 cm increments, were selected based on an internal pilot study. This resulted in 15 pairwise comparisons (${}_6C_2 = 15$), with each participant completing two repetitions per comparison in a random order, yielding a total of 30 choices per participant. For all feedback conditions, the frequency was fixed at 200 Hz and the intensity at 100%, with only the CL values varying.

2) Results: We converted the number of times a specific CL value was chosen as smoother into relative smoothness scores and used them for analysis. To examine whether smoothness scores vary significantly across CL values, we conducted a repeated measures ANOVA. First, Mauchly's test of sphericity confirmed that the assumption of sphericity was met (*i.e.* $p > 0.05$). Then a repeated measures ANOVA demonstrated a significant effect of CL on smoothness scores, with $F(5, 155) = 9.915, p = 3.04e^{-8}$.

TABLE III

BONFERRONI-CORRECTED PAIRED T-TEST P-VALUES FOR INTENSITY-LEVEL SMOOTHNESS COMPARISONS WITH CONTINUITY LENGTH (CL) OF 5 CM.

Intensity	60%	70%	80%	90%	100%
50%	1.000	0.098	**0.012**	**3.0e-6**	**1.2e-6**
60%	-	1.000	0.899	**6.8e-4**	**1.9e-4**
70%	-	-	1.000	**0.003**	**0.001**
80%	-	-	-	0.119	**0.025**
90%	-	-	-	-	1.000

*Significant values ($p < 0.05$) are highlighted in **bold**.

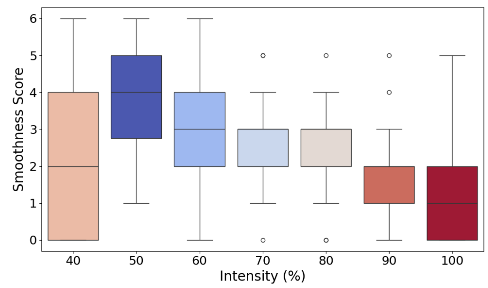


Fig. 6: **Box plots of smoothness scores for intensity values with continuity length (CL) of 5 cm.** All feedback stimuli were delivered at a constant frequency of 200 Hz.

The 40% intensity is excluded from the analysis due to its high standard deviation. Smoothness scores for intensities of 50%, 60%, and 70% are significantly higher than those for 90% and 100%, while 80% is considered to be on the boundary of smoothness perception.

To identify specific CL pairs with significant differences in smoothness perception, we conducted Bonferroni-corrected paired t-tests. The Bonferroni-corrected paired t-tests indicate significant differences in smoothness scores between several CL pairs, specifically (0 cm, 4 cm), (0 cm, 5 cm), (1 cm, 4 cm), (1 cm, 5 cm), (2 cm, 4 cm), (2 cm, 5 cm), (3 cm, 4 cm), and (3 cm, 5 cm), as shown in Tab. I. The box plot for all CL values is presented in Fig. 4. This analysis reveals a significant difference in smoothness perception between CL values of {0 cm, 1 cm, 2 cm, 3 cm} and {4 cm, 5 cm}. Additionally, since a CL of 5 cm shows a smaller standard deviation than 4 cm, we used 5 cm for all conditions in subsequent experiments. Note that since no significant differences were observed for lengths beyond 5 cm in the internal pilot study, the experiment is limited to this range.

D. Experiment 2: Finding Optimal Intensity values for Smoothness Perception

1) Process: In this experiment, we identified candidate intensity values that produced a significant difference in smoothness. We tested a total of eight intensity values, ranging from 30% to 100% in 10% increments. All feedback stimuli were delivered at a constant frequency of 200 Hz. The intensity values were selected using a modified 2-AFC experiment that is similar to the first experiment, but included an additional response option. Participants were asked to choose from three options: whether the first feedback feels smoother, the second feedback feels smoother, or whether at least one of the feedbacks is not perceived at all. The third option is included to account for individual differences in intensity perception thresholds and to prevent participants from evaluating smoothness for feedback that they cannot perceive. Therefore, intensity values that are generally undetectable by participants are excluded from the analysis. The experiments for intensity were conducted for two different CL conditions: without CL and with CL of 5 cm.

2) Results: Before comparing intensity values, we first analyze instances where participants selected the third option that at least one of the feedbacks is not perceived. The results show that, when CL is not applied, 30% intensity is reported as not perceived in 82.59% of cases, 40% intensity in 42.86%, 50% intensity in 11.16%, and 60% intensity in 5.80%. When a CL of 5 cm is applied, 30% intensity is not perceived in 80.36% of cases, 40% intensity in 44.20%, 50% intensity in 9.38%, and 60% intensity in 3.57%. In both conditions, the lower intensity values were always selected as 'not perceived' in any instance. An intensity of 30% is considered a stimulus that may not be perceived by humans, regardless of the presence of CL, as the percentage of unfelt responses exceeded 50%. Therefore, we exclude 30% from the analysis and evaluate the smoothness scores from the remaining intensities.

Additionally, 40% intensity is identified as the second most unfelt level after 30%, with over 40% of participants reporting it as unfelt, regardless of the presence of CL. As shown in Fig. 5 and Fig. 6, the standard deviation for 40% is significantly higher compared to other intensity levels. The high standard deviation observed at 40% intensity can be explained by verbal surveys. During verbal surveys, some participants reported that 40% intensity was too weak to clearly perceive the feedback, making it difficult to rate as smooth. On the other hand, others felt that the weaker the intensity, the smoother the feedback. Therefore, 40% intensity was also excluded from the analysis as it had a relatively high probability of being unfelt and could be interpreted differently among individuals.

To determine whether smoothness scores differed significantly across different intensity values, we first conducted Mauchly's test for sphericity, followed by a repeated measures ANOVA. Mauchly's test indicated that the assumption of sphericity was met for both conditions, with and without CL, as the p-values exceeded 0.05. Consequently, the results of repeated measures ANOVA was $F(6, 186) = 13.7006, p = 7.26e-13$ for the condition without CL, and $F(6, 186) = 11.0779, p = 1.50e-10$ for the condition with CL. These findings confirm that smoothness scores vary significantly with intensity levels, independent of the presence of CL. To identify which intensity values showed significant differences, we conducted a Bonferroni-corrected paired t-test. The results are presented in Tab. II for the condition without CL and Tab. III for the condition with CL.

Based on the results, it is reasonable to suggest that smoothness differences can be categorized into two main groups: the lower intensity group {50%, 60%, 70%, 80%} representing smooth and the higher intensity group {90%, 100%} representing less smooth in the absence of CL. When CL was applied, significant differences were observed between 50% and 80%, as well as between 80% and 100%. However, 80% intensity did not demonstrate significant differences from any other intensity levels. These findings suggest that when CL = 5 cm, intensity levels can be classified into two perceptual categories: a smooth group (50%, 60%, 70%) and a less smooth group (90%, 100%), with 80% serving as the boundary between these two groups. Therefore, we selected 100% as the representative intensity for the less smooth group and 50% as the representative intensity for the smooth group, regardless of the presence of CL.

E. Experiment 3: Matching Perceptual Intensity Between 50 Hz and 200 Hz

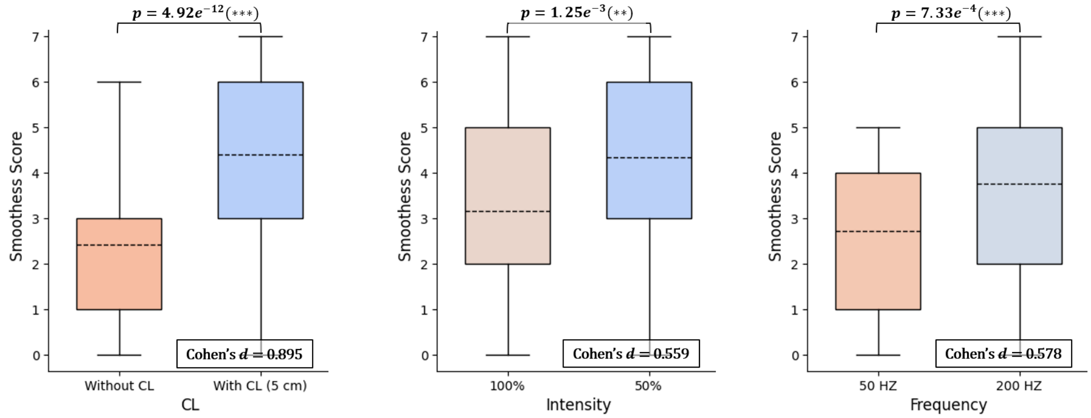
1) Process: In this experiment, we determined the output intensity for 200 Hz which produces a perceived intensity similar to the perceived intensity of 50 Hz at 100% output intensity. We achieved this through an intensity matching task using a 2-AFC adaptive staircase procedure from [30]. In each trial, participants were presented with two consecutive feedbacks: a 50 Hz reference stimulus and a 200 Hz comparison stimulus. The intensity of the 50 Hz feedback was fixed at its maximum level of 100%, while the intensity of the 200 Hz stimulus varied depending on the participants' responses. Participants were asked to report which of the two stimuli felt stronger. 200 Hz stimulus intensity was varied by 20%, then by 10%, and finally by 5%, with adjusting step sizes as reversals occurred, ensuring faster convergence toward the perceptually equivalent output intensity. The staircase procedure ended after ten reversals, and the average of the last eight intensity values at which reversals occurred was calculated.

2) Results: The results show that, without CL, the output intensity of the 200 Hz stimulus perceived as identical to the 50 Hz stimulus at 100% output intensity was approximately 80% (mean: 80.03, standard deviation: 10.71). When CL was applied (CL = 5 cm), the perceptually identical output intensity of the 200 Hz stimulus was approximately 70% (mean: 70.42, standard deviation: 9.80).

F. Discussion

This preliminary study was conducted to determine the appropriate parameter values for comparing tactile perceptions in response to RQ1. Specifically, we aimed to identify suitable values for CL, intensity, and frequency that could effectively differentiate perceived smoothness in the main study.

For CL, values of 0 cm, 1 cm, 2 cm, and 3 cm resulted in statistically similar smoothness perceptions, whereas 4 cm and 5 cm were perceived as significantly smoother. Given this distinction, 0 cm was selected to represent the "less smooth" condition, and 5 cm was chosen to represent the "smooth" condition in the main study.



(a) (b) (c)

Fig. 7: **Box plots of smoothness scores for CL, intensity, and frequency.** (a) Cohen's d analysis for CL, showing a large effect size ($d = 0.895$) when comparing conditions without CL and with CL. (b) Cohen's d analysis for intensity, indicating a medium effect size ($d = 0.559$) between 100% and 50% intensity conditions. (c) Cohen's d analysis for frequency, showing a medium effect size ($d = 0.578$) between 50 Hz and 200 Hz conditions. To ensure comparable perceived intensity, the 200 Hz stimuli were adjusted to 80% intensity for the 0 cm CL condition and 70% intensity for the 5 cm CL condition. These results demonstrate that CL has a greater impact on smoothness perception compared to intensity and frequency.

For intensity, at 30%, the output was too weak to be perceived, and at 40%, participant responses varied widely, leading to a high standard deviation. Therefore, both 30% and 40% intensities were excluded from further analysis. For the remaining intensities, when CL was not applied, 50%, 60%, and 70% were perceived as smoother than 80%, 90%, and 100%. When CL = 5 cm, with 50%, 60%, and 70% significantly smoother than 90% and 100%. Regardless of the presence of CL, 50% consistently resulted in the highest smoothness scores, while 100% had the lowest. Thus, for RQ1, 50% and 100% were selected as representative intensity levels.

For frequency, when CL was not applied, 200 Hz at 80% output intensity produced a perceived intensity comparable to 50 Hz at 100% output intensity. When CL = 5 cm, the perceived intensity of 200 Hz at 70% output intensity matched that of 50 Hz at 100% output intensity.

VI. Main Study

The main study aims to address the three research questions mentioned in Sec.V. The study consists of three experiments, each corresponding to one of the research questions. The first experiment explores which parameter among continuity length (CL), intensity, and frequency has the most dominant influence on smoothness perception. The second experiment examines whether movement-adaptive haptic rendering conveys continuity and smoothness more effectively compared to a conventional fixed-direction approach. In the final experiment, we apply the proposed haptic rendering method in interactions with various virtual objects to evaluate its effectiveness in expressing smoothness and its impact on the haptic experience.

A. Participants

For the main study, 31 participants aged 20 to 34 years were recruited (22 males, 9 females; mean age: 24.23 years, standard deviation: 3.33). Among them, 11 participants had used the Ultraleap device 1–2 times, while one participant had used it more than 5 times; the remaining participants had no prior experience with the device. The group included 29 right-handed and 2 left-handed participants, all of whom had no skin conditions on their palms. The study was approved by the Institutional Review Board (IRB) of KAIST (IRB approval no. KH2024-184), and all participants provided informed consent before participation.

B. Experimental Setup

The experimental settings for the main study were nearly identical to those in the preliminary study, except for differences in the red marker display. In the first experiment of the main study, the setup was identical to the preliminary study. However, in the second experiment, the red marker moved not only left and right but also in other directions, causing the hand movement direction to follow accordingly. In the third experiment, the red marker was removed, with a virtual object and a virtual hand visualized on the screen instead.

C. Experiment 1: Identifying the Dominant Parameter Affecting Smoothness Perception

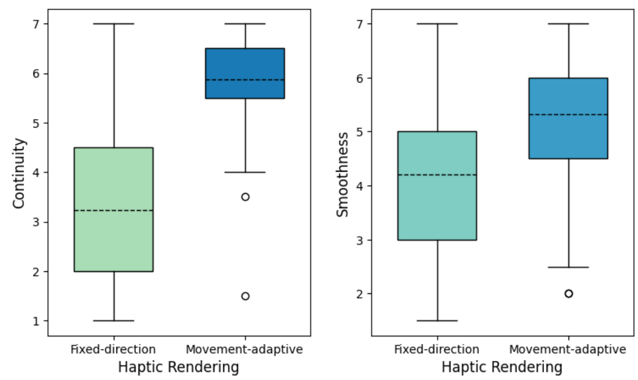
1) Process: The first experiment of the main study was designed to investigate which parameter—continuity length (CL), intensity, or frequency—had the greatest impact on smoothness perception. This experiment employed the same 2-AFC (Two-Alternative Forced Choice) method as the first experiment of the preliminary study. A virtual sphere with a diameter of 30cm was used as the target object, consistent with the preliminary setup. To compare perceived smoothness, CL was set to a condition without CL and a condition with CL applied at 5 cm, while intensity was set to 50% and 100%. However, since a direct comparison based solely on frequency values was not feasible due to variations in perceived intensity, we incorporated the findings from the third experiment of the preliminary study. Therefore, we selected the following eight feedback combinations for the experiment, representing the three parameters CL, Frequency, and Intensity: (0 cm, 50 Hz, 100%), (0 cm, 200 Hz, 80%), (5 cm, 50 Hz, 100%), and (5 cm, 200 Hz, 70%), (0 cm, 200 Hz, 50%), (0 cm, 200 Hz, 100%), (5 cm, 200 Hz, 50%), and (5 cm, 200 Hz, 100%). To generate all possible comparisons, we paired each condition with every other condition, producing 28 unique pairs ($_8C_2 = 28$) in a random order. Each participant evaluated all 28 pairs, selecting which feedback felt smoother in each comparison.

2) Results: A mixed linear model regression was applied to investigate the interaction effects among CL, intensity, and frequency. The assumptions of linearity, homoscedasticity and normality of residuals were verified before conducting the analysis. The interaction term between frequency and intensity was excluded due to high multicollinearity, as indicated by variance inflation factor (VIF) values of 39.36. Additionally, since frequency and intensity were adjusted to achieve the same perceived intensity in the third experiment of the preliminary study, including their interaction was unnecessary. Furthermore, the interaction effects between CL and frequency ($p = 0.07$) and CL and intensity ($p = 0.181$) were not statistically significant. Based on these findings, we focused on analyzing only the main effects.

To investigate the main effects, bonferroni-corrected paired t-tests were conducted. The results demonstrate statistically significant differences for all parameters, as shown in Fig. 7. Although all pairwise comparisons had extremely small p-values, Cohen's d was used to evaluate and compare the effect sizes of CL, frequency, and intensity on perceived smoothness. The results of Cohen's d analysis revealed that the difference in smoothness between the conditions without CL and with CL had a Cohen's d value of 0.895, as in Fig. 7a, indicating a large effect. Additionally, when comparing the intensity conditions of 100% and 50%, the Cohen's d value was 0.559, and when comparing the frequency conditions of 50 Hz and 200 Hz, the Cohen's d value was 0.578. This frequency comparison was specifically conducted between (0 cm, 50 Hz, 100%) and (0 cm, 200 Hz, 80%) as well as (5 cm, 50 Hz, 100%) and (5 cm, 200 Hz, 70%), with intensity values pre-adjusted to produce a similar perceived intensity across frequencies, as identified in Experiment 3 of the preliminary study. This adjustment was made to ensure that the differences in perceived smoothness could be attributed to frequency itself, rather than to the differences in perceived intensity. Both values indicate medium effect sizes, as shown in Fig. 7b and Fig. 7c. Therefore, CL has the greatest impact on smoothness perception, suggesting that CL is more suitable for representing smoothness than traditional roughness-based parameters.

D. Experiment 2: Comparing Movement-Adaptive and Fixed Direction Haptic Rendering for Enhanced Smoothness with CL

1) Process: This experiment aims to investigate whether movement-adaptive haptic rendering provides a more continuous and smooth tactile sensation compared to fixed-direction haptic rendering. To test this, we divided the haptic feedback into two types: (1) fixed-direction feedback, where the feedback point moved at a constant speed of 10 cm/s to the right in a palm-centered coordinate system, and (2) our proposed movement-adaptive haptic rendering, which adjusts the contact point in exactly opposite direction to the user's hand movement based on CL. Since the continuity of the fixed-direction feedback could be influenced by the direction of hand movement, we classified the hand movement into three distinct directions: left-right (LR), forward-backward (FB), and circular (CC) movement. In the experiment, participants interacted with a virtual sphere displayed on a screen for 10 seconds. The sphere had a diameter of 30 cm, providing a consistent haptic target across experiments. The haptic feedback was delivered at a fixed frequency of 200 Hz and an intensity of 100% throughout the experiment. Afterward, they completed a questionnaire assessing the haptic feedback, which included two statements: (1) "The haptic feedback felt continuous" and (2) "The haptic feedback felt smooth" Responses were recorded on a 7-point Likert scale.

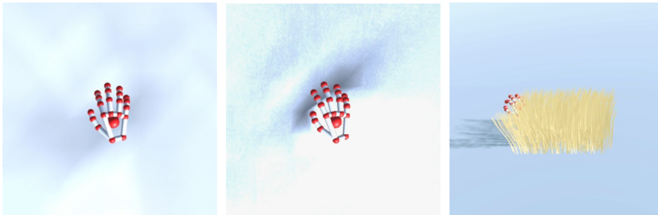


(a) (b)

Fig. 8: **Box plots of continuity and smoothness scores for fixed-direction and movement-adaptive haptic rendering.** (a) Continuity scores ($p = 1.07e^{-23}$), (b) Smoothness scores ($p = 8.01e^{-10}$), both showing significant differences, indicating the superiority of movement-adaptive rendering.

2) Results: To assess whether hand movement direction affects the perception of continuity and smoothness in fixed-direction haptic rendering, we conducted Mauchly's test of sphericity followed by a repeated measures one-way ANOVA across LR, FB, and CC directions. Mauchly's test indicated sphericity violations for both continuity ($p = 1.17e^{-17}$) and smoothness ($p = 1.46e^{-11}$), so the Huynh-Feldt correction was applied. The corrected ANOVA showed no significant effect of direction on continuity ($p = 0.079$) or smoothness ($p = 0.066$). A similar analysis for movement-adaptive haptic rendering also found no significant effects, with $p = 0.993$ for continuity and $p = 0.650$ for smoothness. These results indicate that hand movement direction does not significantly impact the perception of continuity or smoothness in either fixed-direction or movement-adaptive haptic rendering.

The next step is to investigate whether significant differences exist in continuity and smoothness scores between movement-adaptive haptic rendering and fixed-direction haptic rendering. The Bonferroni-corrected paired t-test revealed significant differences between the two rendering methods,



(a) (b) (c)

Fig. 9: **Visual rendering of virtual objects used in Experiment 3 of the main study.** (a) Silk, (b) Velvet, and (c) Fur. The red hand represents the visualization of the user's hand.

with p-values of $8.01e^{-10}$ for continuity and $1.07e^{-23}$ for smoothness, both far below the 0.05 threshold, as shown in Fig. 8. This implies that incorporating hand movement in haptic rendering significantly contributes to both increased continuity and smoothness.

E. Experiment 3: Applying CL-Based Movement-Adaptive feedback in Virtual Object Interaction

1) Process: The final experiment aims to demonstrate the applicability of movement-adaptive haptic rendering in various virtual object interaction scenarios. In this experiment, silk, velvet, and fur were chosen as virtual objects based on preliminary verbal surveys, where participants identified them as representative of fabric and fur textures. The visual rendering for the silk and velvet was implemented using the cloth component provided by the Unity game engine, with textures downloaded from a copyright-free online resource, while the fur was modeled and implemented using a particle-based approach, as shown in Fig. 9. To minimize the influence of visual factors beyond surface texture, the overall shape, lighting conditions, and base color of the silk and velvet materials were kept consistent. However, their surface reflectance properties were deliberately varied to convey distinct material impressions. The silk texture was designed with a high specular component to produce a smooth and glossy appearance, while the velvet texture featured a low reflectance to achieve a matte visual impression. Both materials were simulated using the same cloth component provided by the Unity game engine, ensuring consistent deformation behavior across conditions during interaction. Participants were instructed to interact freely, and the speed and path of their hand movements were recorded.

The experiment was conducted under three feedback conditions for each virtual object: (1) without CL, (2) with CL in a fixed direction, and (3) with CL dynamically adjusted to align with hand movement. All haptic feedback was delivered at a constant frequency of 200 Hz and intensity of 100% across all conditions. The survey was developed based on the Haptic Experience (HX) questionnaire [31] and included an additional item to assess feedback: "The tactile feedback accurately represented the smoothness of the object." As a result, the survey comprised six questions:

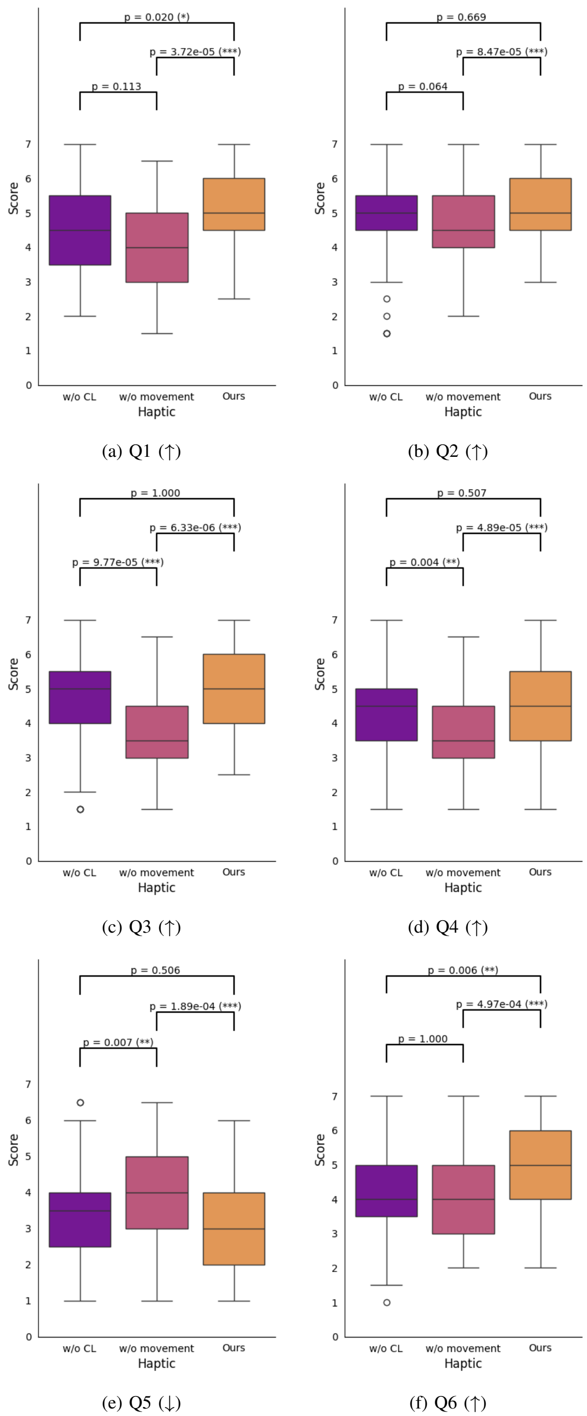
- I like having the haptic feedback as part of the experience.
- The haptic feedback changes depending on how things change in the system.
- The haptic feedback increased my involvement in the task.
- The haptic feedback was realistic in my own experience.
- The haptic feedback was disconnected from the rest of the experience.
- The haptic feedback well represented the smoothness of the object.

Each participant experienced all combinations of three feedback conditions and three virtual objects, with every combination presented twice to ensure robustness. This resulted in a total of 18 trials per participant. The order of the trials was fully randomized to minimize order effects. After each trial, participants completed a 7-point Likert scale survey consisting of six questions, allowing us to assess each feedback-object pairing individually without aggregating responses across different conditions or materials.

2) Results: To assess whether the ratings for each question differed across virtual object types, we fitted a linear mixed-effects model for each question, including participant as a random effect and virtual object as a fixed effect. Estimated marginal means were computed for each virtual object, and post-hoc pairwise comparisons were conducted using model-based standard errors. Across all six questions, none of the pairwise contrasts between Silk, Velvet, and Fur reached statistical significance, with all p-values exceeding 0.05. These results suggest that the type of virtual material did not significantly influence the perceived quality of the haptic feedback. Therefore, subsequent analyses and discussions are based on the overall scores, as no significant differences were found between virtual object types.

Using repeated measures ANOVA, we examined whether there were significant differences between the haptic rendering methods for each question. Before the analysis, Mauchly's test of sphericity was conducted, which revealed violations of sphericity for all items. Given that the Greenhouse-Geisser epsilon values exceeded 0.75, the results of the Huynh-Feldt corrected RM ANOVA were analyzed. The p-values for each question were as follows: $Q1 : 1.65e^{-10}, Q2 : 9.84e^{-4}, Q3 : 2.03e^{-6}, Q4 : 4.04e^{-5}, Q5 : 6.17e^{-5}$, and $Q6 : 8.49e^{-4}$. These results indicate significant differences between the haptic rendering methods for all questions.

To identify which haptic rendering methods differed, we conducted post-hoc pairwise comparisons. Fig. 10 visualizes the differences in haptic rendering for each condition using box plots, including both significant and non-significant p-values for a comprehensive overview. Except for Q5, higher scores indicate a more positive evaluation across all other questions.
for circular and linear motion counts were 0.62 and 2.81, with standard deviations of 0.70 and 1.16, respectively. Although hand movement velocity showed high variability, the use of mixed-effects models, which account for individual differences and emphasize overall trends, mitigates concerns about such fluctuations. None of the features significantly affected the responses, and the regression coefficients for velocity were consistently close to zero, indicating a negligible impact across



(a) Q1 (↑) (b) Q2 (↑)

(c) Q3 (↑) (d) Q4 (↑)

(e) Q5 (↓) (f) Q6 (↑)

Fig. 10: **Box plots of questionnaire responses comparing movement-adaptive and fixed-direction haptic rendering.** Box plots illustrating response differences for each question. (a) Q1, (b) Q2, (c) Q3, (d) Q4, (e) Q5, and (f) Q6. Each plot includes both significant and non-significant p-values for a comprehensive overview. Higher scores indicate a greater positive effect, except for Q5.

all questions. These results suggest that the observed perceptual differences are unlikely to be explained by variations in movement patterns.

The results demonstrated that our proposed CL-based movement-adaptive haptic rendering was significantly superior to the fixed-direction approach across all questions. Specifically, our method showed significant differences in Q1 and Q6, suggesting that it is preferred over less smooth feedback without CL and effectively conveys the smoothness of cloth and fur. Additionally, the fixed-direction approach, which lacks CL and selects local maxima as feedback points at each timestep, showed significant differences in Q3, Q4, and Q5. This indicates that static feedback in active touch scenarios may negatively impact immersion, realism, and harmony.

VII. Discussion

The findings from the main study highlight three key aspects: the effectiveness of our proposed parameter, continuity length, in expressing smoothness; the necessity of CL-based movement-adaptive haptic rendering; and the applicability of this approach in interactions with virtual objects. In this discussion, we summarize the implications of these results.

A. Main Study 1: Identifying the Dominant Parameter Affecting Smoothness Perception

The findings from the first main study underscore the critical role of continuity length in smoothness perception. It turned out to be the most influential factor, surpassing the impact of intensity and frequency. This suggests that maintaining consistent contact by applying CL significantly enhances the perception of smoothness in tactile feedback. While intensity and frequency contribute to the overall experience, their effects were comparatively minor. These insights are particularly valuable for haptic system design, highlighting the importance of prioritizing CL to optimize smoothness in user interactions.

B. Main Study 2: Comparing Movement-Adaptive and Fixed Direction Haptic Rendering for Enhanced Smoothness with CL

The second study highlights the importance of adapting haptic feedback to user movements. The results showed that movement-adaptive haptic rendering is more effective than fixed direction rendering in delivering both continuous and smooth tactile sensations. This suggests that considering the natural dynamics of hand movements significantly enhanced the user experience by providing smoother feedback. These findings reinforce the need for dynamic rendering techniques that adapt to hand movement in haptic systems, not only to enhance immersion but also to optimize perception.

C. Main Study 3: Applying CL-Based Movement-Adaptive feedback in Virtual Object Interaction

The applicability of CL-based movement-adaptive haptic rendering across various virtual objects demonstrates its versatility and effectiveness in diverse scenarios. The results indicate that incorporating continuity length (CL) not only enhances smoothness but also promotes a preferable experience. Integrating hand movement into active virtual interactions has a positive impact on the overall haptic experience while significantly contributing to smoothness perception. Although no statistically significant differences were found between virtual object types, this may be due to the similarity in overall smoothness profiles rendered by the CL-based method across materials. The lack of significant effects from hand movement features may be attributed to the robustness of the movement-adaptive rendering, which maintains feedback continuity regardless of individual movement patterns.

D. Limitations

While the proposed CL-based movement-adaptive haptic rendering demonstrates promising results, this study has several limitations.

First, the proposed continuity length (CL) parameter was applied exclusively within the context of movement-adaptive haptic rendering. As such, its effectiveness and applicability in other haptic rendering paradigms remain untested. In this study, CL was evaluated under a specific strategy in which feedback is rendered at the local maximum of a simulated pressure field. While this configuration was effective in revealing the perceptual impact of CL under controlled conditions, further work is needed to examine whether similar effects hold in alternative rendering approaches, such as fixed-point or multi-point feedback strategies.

Second, while this study emphasizes the effectiveness of continuity length (CL) in supporting spatiotemporal continuity during active touch, further investigation is needed to better understand its specific role in spatial continuity. In particular, the current implementation renders feedback at the local maximum of a simulated pressure field, which enables the feedback point to follow the hand's motion across space. However, it remains unclear how CL compares with alternative strategies that do not prioritize spatial continuity. For example, approaches that consistently render feedback at the center of the pressure field may reduce positional variability across frames but may not align with the actual exploratory path of the hand. Conducting controlled comparisons between movement-adaptive and spatially invariant feedback strategies may help clarify how maintaining spatial continuity in haptic rendering affects perception, which could guide future research.

Third, the participant pool was limited to individuals aged 20–34. Given potential age-related differences in tactile sensitivity, the findings may not generalize to other age groups.

Fourth, individual-level effects were not analyzed. Although the sample size supports group-level conclusions under normality assumptions, personalized adaptation of CL parameters remains an open direction.

Fifth, the evaluation was limited to a single-session exposure. Long-term effects, including potential learning, adaptation, or habituation to CL-based feedback, were not considered and warrant future study.

Sixth, while CL-based feedback yielded statistically significant differences in perceived smoothness, its functional impact in real-world VR contexts—such as gaming or training—remains to be explored. Statistical significance alone does not guarantee practical utility in complex usage scenarios.

Lastly, cross-modal interactions between visual and haptic cues were not explicitly investigated. Although visual material properties were manipulated through reflectance, their influence on haptic perception was not isolated. Future work should examine how visual-tactile congruence shapes user perception in multisensory environments.

E. Beyond Ultrasound Haptic System

To achieve high haptic resolution and directional expressiveness, this study was conducted using ultrasound amplitude modulation as the haptic rendering method. However, this approach is not inherently limited to ultrasound devices. Any haptic technology capable of high-resolution feedback and precise directional control, such as hydraulic-based systems, could potentially adopt CL-based rendering to achieve similar results. Since continuity length (CL) is designed to ensure both temporal and spatial continuity in tactile feedback, its core concept is compatible with various actuation technologies that can support dynamic and localized stimulation. This suggests broader applicability across different haptic technologies beyond ultrasound-based systems.

VIII. Conclusion

In this study, we introduce continuity length (CL) as a key parameter influencing smoothness perception in haptic rendering. Our findings confirm that applying CL significantly enhances the perception of smoothness compared to conditions without it. This effect is more pronounced than that of traditional haptic parameters such as intensity and frequency, which have primarily been used to represent roughness. Additionally, we found that a movement-adaptive haptic rendering method, which dynamically shifts the feedback point in the direction opposite to hand velocity, enhances the perception of continuity and smoothness more effectively than a fixed-direction feedback approach. Furthermore, our proposed CL-based haptic rendering method was highly effective in conveying smoothness across interactions with various virtual materials, including silk, velvet, and fur.

These insights highlight the importance of CL as a critical parameter for fine-tuned control over smoothness perception, thereby expanding the expressive capabilities of haptic systems. These insights highlight the importance of CL in enabling both temporal and spatial continuity in active touch scenarios, which are essential characteristics of smooth tactile experiences. By integrating CL with adaptive feedback mechanisms, future research can further refine haptic rendering techniques and enhance user experience in virtual environments.

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