Masque: Exploring Lateral Skin Stretch Feedback on the Face with Head-Mounted Displays

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Figure 1. Masque is a prototype HMD integrating with six skin stretch modules. (a) Six shear tactors are placed on the facial interface and can generate 2-degree-of-freedom lateral skin stretches, (b) which enables various skin stretch feedback or directional cues in virtual reality.

ABSTRACT
We propose integrating an array of skin stretch modules with an head-mounted display (HMD) to provide two-dimensional skin stretch feedback on the user's face. Skin stretch has been found effective to induce the perception of force (e.g. weight or inertia) and to enable directional haptic cues. However, its potential as an HMD output for virtual reality (VR) remains to be exploited. Our explorative study firstly investigated the design of shear tactors. Based on our results, Masque has been implemented as an HMD prototype actuating six shear tactors positioned on the HMD's face interface. A comfort study was conducted to ensure that skin stretches generated by Masque are acceptable to all participants. The following two perception-based studies examined the minimum changes in skin stretch distance and stretch angles that are detectable by participants. The results help us to design haptic profiles as well as our prototype applications. Finally, the user evaluation indicates that participants welcomed Masque and regarded skin stretch feedback as a worthwhile addition to HMD output.

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INTRODUCTION
Head-mounted displays, or HMDs, have been proven effective in providing users with immersive visual and audio experiences in virtual reality (VR). To further enrich VR experiences, recent studies proposed integrating haptic modules within HMDs to generate various sensory outputs directly onto the face, for example, vibrotactile [20], thermal [29, 28, 6, 35], suction [19] and force feedback [15, 5]. User evaluations from these studies suggest that HMD-enabled haptic feedback enhances the enjoyment and immersivity of VR applications.

In this paper, we propose integrating an array of skin stretch modules on an HMD to produce *skin stretch feedback* on the face. After a user wears on the HMD, the modules' shear contactors (or *shear tactors*) press on the facial skin. Actuating the tactors causes lateral skin stretch, which delivers rich haptic information to the user, including the distance and angle of the skin stretch. Researchers have found that skin stretch is especially useful to create force illusions (*e.g.*, weight and inertia of an object [26]) and to deliver directional information on fingertips [39, 12, 13, 14]. However, applying skin stretch feedback on the surface of the face remains to be exploited.

On human faces, a quick skin stretch generated by an HMD allows users to experience a graze in a snowball fight (Figure 11), while long-term leftward skin deformations around the eyes can simulate the inertia effect during a motorcycle race (Figure 10). The stretch directions can also inform the user where to go at in a virtual museum (Figure 12). Even more interestingly, the tactor can be used to interfere with facial expressions; this may be achieved for example by stretching the skin near the corners of the eye to make the wearer perceive difficulty in fully opening his or her eyes after getting a direct virtual snowball hit (Figure 11). This is in accordance with recent VR works that explore producing body constraints [1] or negative emotions [22], which results in even more fun and realistic VR experiences.

Developing skin stretch feedback for the human face creates a number of design challenges and scientific questions in regard to human perception. An exploratory study was conducted to understand exactly what should be considered for the design of the shear tactors. Based on participants' suggestions, we implemented an prototype HMD, named *Masque*. As illustrated in Figure 1a, Masque is augmented using six shear tactors applied to the face via the interface of an HMD. Each tactor is actuated by a pair of motors, capable of producing two-degree-of-freedom shear movements. When a tactor is actuated, the skin underneath the tactor moves along with the tactor itself, causing skin stretch feedback (Figure 1b).

We first evaluated the physical comfort of the skin stretches generated by our prototype device. The results helped us to ensure that our prototype generates physically acceptable skin stretch feedback.

In the psychophysical studies, we examined the Just Noticeable Difference (JND) values. Two crucial factors, the location and the direction of skin stretch, were considered for the studies. We first explored the minimum change of skin stretch distance that is detectable by users, as many VR games or movies often have scenarios that involve different levels of haptic feedback. The results revealed an average JND of 24.6% across all the tested conditions. The results also reveal that the JND was not affected by different stretch locations or directions of skin stretches. We then examined the discrimination threshold of the angles of different skin stretches. The results suggest that participants could discriminate at least eight directions at each sample location. Finally, to demonstrate our interaction techniques, we developed three VR applications tailored for Masque. Users' experiences with these applications then formed the basis for a user evaluation conducted to gain an understanding of HMD-enabled skin stretch feedback.

The primary contributions of our work are: (1) the concept of creating lateral skin displacement by physically stretching the contact skin; (2) the results of user studies that investigate the capabilities of skin stretch on the surface of the face; (3) the implementation of Masque, a proof-of-concept prototype; (4) a set of applications that demonstrate that concept; (5) the results of a preliminary user evaluation of this new haptic HMD prototype.

RELATED WORK

Skin Stretch Feedback

When a shear force is applied to the skin, it causes lateral skin deformation and creates skin stretch feedback. Such feedback is often used for enhancing the experience of virtual object interaction or directional guidance.

The skin stretch feedback induces perception of force [9, 27]. Provancher *et al.* mounts a shear tactor on a PHANToM device and find that such a configuration could increase the perception of friction on the fingertip [30]. Similarly, Quek *et al.* implements a pen-shaped device augmenting an one-dimensional shear display [31]. When pulling down on the device, the shear display moves according to the normal forces applied on the virtual surface, which can simulate different levels of stiffness of a virtual object underneath the pen. The subsequent works utilized stretch displays a higher degree of freedom (3-DoF [32] or 6-DoF [33]) to substitute force and torque feedback.

For teleoperation or VR applications, researchers usually adopt a finger-grounded configuration, in which the tactor is applied against the fingerpad and driven by the motors on the fingernail. For example, Minamizawa *et al.* propose using finger-worn belts for skin stretches [26]. When grabbing a virtual object, the combinations of skin stretch feedback to grasp fingers simulate the weight and inertia of objects. Others have proposed more complex mechanical designs to enable 2-DoF [41, 11] and 3-DoF skin deformations [23, 24, 38, 37]. Comprehensive reviews of these designs can be found at [9, 27].

Lateral skin deformation is also found effective in delivering directional cues. Bark *et al.* shows that on communicating directional cues, skin stretch is more effective than vibration feedback [3]. Researchers have investigated the users' capability to distinguish directions of stretches on fingertips, and this research has found that participants can at least distinguish four directions of skin stretch [39, 12, 13, 14]. In addition to research on the fingertips, other researchers also have proposed generating skin stretch on the palm [16], wrist and forearm [7, 40, 18, 4, 8] for guidance and navigation tasks.

Despite plentiful research in regard to findings on skin stretch feedback, previous studies mainly focus on generating skin stretch feedback on fingers or limbs. How to generate different levels of skin stretch feedback on the surface of the face remains unexplored. As an initial exploration, in the first psychophysical study, we examined the discrimination thresholds of skin stretch distances on the face. In the second psychophysical study, we examined the discrimination thresholds of skin stretch angles on the face.

HMD-Enabled Haptic Output

Previous works have suggested integrating various haptic modules on HMD for guidance or enhancing the immersivity in VR.

For guidance, prior works integrate an array of vibrational tactors on the HMD, which can produce spatial and temporal haptic feedback on the head [10, 20, 17]. Peiris *et al.* placed thermal modules on the face interface of an HMD and designed thermal patterns as directional cues [29].

Thermal and wind feedback immerses users into the virtual world. Ambiotherm uses the thermal and wind modules to simulate the environmental conditions in VR [34]. Ambient enhances the experience of remote presence that consists of a fully facial thermal feedback system combined with the first person view [35] Combining the thermal feedback with vibrotactile feedback, LiquidReality generates wetness sensations on the face for underwater scenarios in VR [28]. ThermoReality also utilizes thermal modules to enhance the user's presence in the virtual reality environment [6].

When interacting with virtual worlds, force feedback creates a more realistic experience. GyroVR is an HMD utilizing a gyroscope interface. When moving the HMD, the gyroscope effect creates tangential forces and the sensation of inertia [15]. Recently, Chang *et al.* proposed a pulley-based mechanism on the HMD to produce normal force on the face [5], which enhances the boxing and diving experiences in VR. Sato *et al.* have discovered the Hanger Reflex phenomenon [36] in which mounting a hanger on the head produces rotational force perception and induces unexpected head rotations. Such a phenomenon would be caused by lateral skin deformation caused by pressure around the head. HangerOver utilizes the Hanger Reflex phenomenon to simulate the experience of being pushed or punched [21]. Haptopus uses a suction mechanism on the face to simulate the haptic feedback of the hand. [19]

In addition, electric stimulus is also effective in enhance immersivity. Aoyama *et al.* proposed placing electrodes around the head. Sending currents to the electrodes induces the perception of virtual acceleration [2]. Kono *et al.* proposed In-Pulse, a prototype HMD that integrates the use of electrical muscle stimulation (EMS) modules to induces virtual experiences of fear and pain [22].

In contrast to previous HMD-enabled haptic feedback, we focus on exploring the skin stretch feedback on the surface of the front face.

DESIGNING SHEAR TACTORS

An informal exploratory study was conducted to help us to design the shear tactors. Two geometry factors of shear tactors, shape and size, were considered in this initial exploration. As displayed in Figure 2a, the shapes of the three circular plates were convex, flat, and concave in shapes, each of which was 3D printed with diameters of 10mm, 20mm, and 30mm respectively. The curvature of the concave and convex tactors was all 0.114 (cm^{-1}) and the thickness of the plates was 5 mm. To increase the friction between the plates and facial skin, the plates were covered with 2mm-thick silicon cover. The softness of silicon covers also increases the comfort when tactors are pressed upon or moved against on the skin. To make the tactor easier to be manipulated by hand, we added a 3D printed handle on the back of each plate (Figure 2b).

Participants and Task

We recruited 12 participants (2 female, 10 male, all between the ages of 22 and 26) to participate the study. The experimenter introduced the usage of the plates and asked the participants to use them to stretch the skin. During the study, the experimenter did not restrict the location, direction, and distance of the skin drag movement. Instead, the participants were encouraged to try as many combinations as they wanted, as long as the skin stretches were preferable. They then responded with preference ratings from 1 to 7 using continuous scale with 1 as least acceptable and 7 as most acceptable. Decimal ratings like 5.7 were permitted. The entire experiment took approximately around 15 minutes.

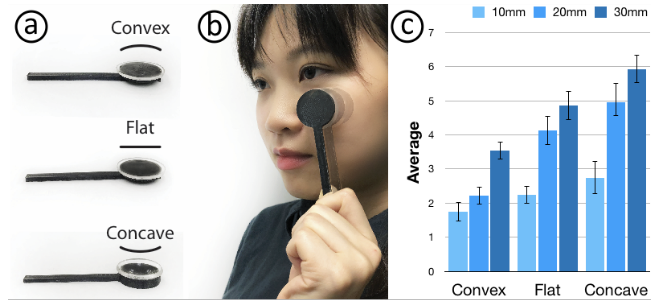

Figure 2. (a) The shear tactors we explored, including convex, flat, and concave shapes. (b) The participant generates skin stretches by the tactors. (c) User preferences regarding the shear tactors. Error bars show a standard error in all figures.

Results

The preference scores for the tactors are displayed in Figure 2c. We conducted a 2-way repeated measured ANOVA on the agreement scores with *Shape* and *Size* as the independent variables. The results indicate no significant interaction between the two independent variables ($F_{2.30,25.28} = 2.41$, $p = 0.104$). However, the results show significant effects in regard to both *Shape* ($F_{1.96,21.57} = 14.24$, $p < .001$) and *Size* ($F_{1.94,21.30} = 56.06$, $p < .001$).

For *Shape*, the pairwise comparison shows that the scores for the concave-shaped tactors are significantly rated higher than convex-shaped tactors ($p < .01$); and the flat-shaped tactors also received significantly higher scores than convex-shaped tactors ($p < .01$). On average, the concave-shaped tactors received the highest scores. This is interesting, as previous works usually adopt flat or convex shapes for the shear tactors on fingertips [12, 14]. Participants report that the concave shape can *"better contact facial skins during movement and cause more clear perceptions of skin stretches (P10)."* They also report that *"concave-shaped tactors are more fitted to the geometry of facial bones such as the supraorbital and cheekbones (P1, P4, P5)."* In contrast, the convex-shaped tactors stretch skin less and sometimes press against the facial bones, resulting in unpleasant sensations when they are in contact with the faces. Due to the similar reasons, the flat-shaped tactors were usually rated in the middle of intermediately in comparison with the rating of the other shapes.

For *Size*, the pairwise comparisons indicate that larger tactor size increases the preference score (all $p < .05$). Participants reported that, when applying the similar shear forces, larger sized tactors results in a larger contact area, which can create more easily perceived skin stretch feedback. Most of the participants regard the 10-diameter tactors unacceptable as they easily induce a tingling pain on their faces.

Considering the statistical results and participants' feedback, we decided to implement the use of the 30mm-diameter, concave-shaped tactors for the hardware prototype, as the average rating for that tactor was rated highest in regard to their preferences.

MASQUE PROTOTYPE

Implementation

We created Masque, a proof-of-concept prototype HMD to demonstrate the novel interaction enabled by the lateral skin stretching. We determined to augment skin stretch modules on an HTC Vive Pro as it covers the largest facial region compared to other popular off-the-shelves HMDs (*e.g.*, HTC Vive, PS VR, and Oculus Rift). Such a configuration allows us to augment more skin stretch modules with larger stretching distances. The number, locations, and maximum moving distance of movement of the skin stretch modules were determined after several attempts. Our final design ensures that every shear tactor can be freely actuated without colliding with any others.

As displayed in Figure 3, three pairs of skin stretch modules were implemented and symmetrically positioned above, on the sides, and below the HMD lenses, where each module contains a shear tactor. Similar to previous works on HMD-enabled haptic outputs [29], the shear tactors are positioned on the facial interface of the HMD. For convenience, the shear tactors of the stretch modules are notated as L1/R1 (top), L2/R2 (sides), and L3/R3 (bottom) (See Figure 3b).

The center of the tactors is located at the center-line of the face interface. The maximum distance of skin stretch is 15 mm in any direction. As describe earlier, each tactor was a 3D printed, concave plate with a diameter of 30mm. Their contact surfaces are covered by a 2 mm-thick sheath of silicon. The Masque prototype communicates with a desktop computer via a serial connection at 115200 baud.

As shown in Figure 3b, the skin stretch module contains two gear motors; one is used for the horizontal movements and the other for the vertical movements. The Pololu 12 HPCB gear motors with gearheads 298:1 are used and can run at a top speed of 100 RPM. The 12 CPR magnetic encoders are mounted on the back shaft of the motors for measuring the speed of the motors. These motors could actuate the tactor at a maximum speed of 63mm/s. A PID loop is implemented for controlling the motors. The PID loop maintains the stretch distance and prevents the motor from being slowed down by the facial skin. The torque of the motors is 70oz-inch. A thirty-eight Newton normal force is needed to stop the tactor, which is enough to resist the normal force from the human face when wearing Masque. The resolution of the tactor movements was 0.1 millimeter. We used 6 mortor drivers (TB6612FNG, SparkFun) that were connected to an Arduino Mega board and communicated with a computer via USB to control these motors.

Reducing Pressure on Front Face

The weight of the hardware components and 3D-printed materials are 225g. When wearing on the device, the additional weight adds to the pressure on the surface of the face, which could affect wears' sensing capabilities when wearing a regular HMD. To resolve this issue, we implemented both ceiling-grounded and body-grounded configurations.

For the ceiling-grounded configuration, we implemented a pulley structure on the ceiling and used it to generated a force lifting-up on the HMD. As shown in Figure 4a, the structure of the pulley system includes a counterweight, pendulums, shafts, and fishing lines as torsion wires. We carefully adjusted the counterweight to cancel out the additional weight from the motors and 3D-printed structures.

Although the ceiling-grounded configuration is effective, it restricts the workspace of wearers. To increase the mobility, we further implemented the body-grounded configuration. As displayed in Figure 4b, the counterweight is mounted on the back strap of the HMD. Leveraging the top of the head as a stand, the configuration also generates an up-lifting force on the HMD. To further reduce the pressure on the top of the head caused by our design, we also removed the built-in headphones on the HMD.

We utilized the ceiling-grounded configuration for the following comfort study and psychophysical studies. As for the user evaluation of the demo applications, the body-grounded configuration was adopted. Although, the body-grounded configuration added more pressure to the top of the head, we did not receive negative feedback in regard to this during the user evaluations.

EVALUATING PHYSICAL COMFORT OF MASQUE

The shear tactors of Masque cover the facial skin surrounding the eyes and nose. Thus, it is essential to ensure that participants stay comfortable when experiencing the skin stretch feedback generated by our mechanical design. This study measured the maximum stretch distances (within 15mm), that are considered physically acceptable by participants. For each tactor, the participants were asked to report the distances in four fundamental directions, *i.e.*, the up, down, left, and right stretches from the original position.

Note that, instead of evaluating maximum tolerance of skin stretches, the aim of this study was to understand how to generate acceptable stretch feedback through Masque and prevent participants experiencing any discomfort in the following study. We regard the examination of the maximum tolerance as an issue to explore in future works.

Participants

Twelve participants (4 females and 8 males) between the ages of 20 and 27 took apart in this study. All of them had had experience using HMDs. During the entire study, the participants wore noise canceling headphones to block the motor noise while in a seated position. For tactor pressures, in a series of pilot studies, we placed pressure sensors below each tactor and asked the participants to adjust the tightness of the HMD until they thought the HMD was highly stable yet comfortable to wear. The average value was approximately 2.5N. Thus, the tightness of the head band was carefully maintained among all participants at approximately 2.5N.

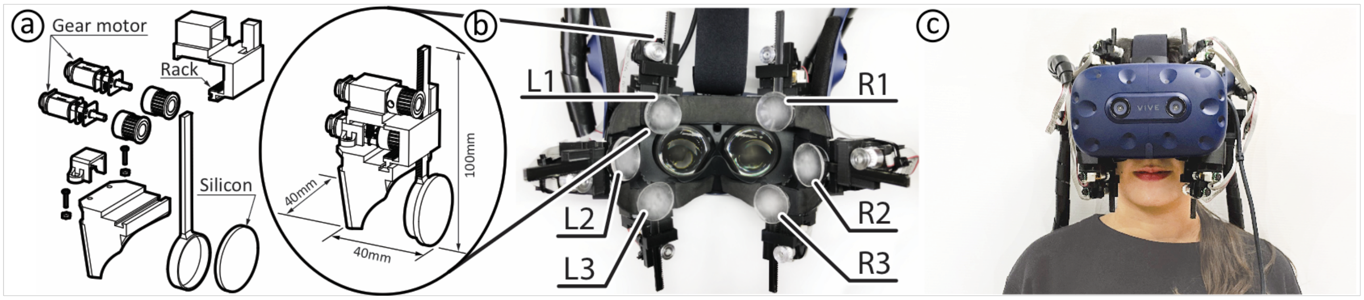

Figure 3. The Masque prototype actuates three pairs of skin stretch modules. The (a) exploded view and (b) the hardware implementation of the skin stretch module. (c) A user wears the Masque prototype.

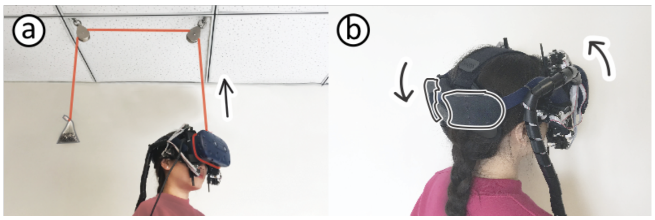

Figure 4. We implemented (a) ceiling-grounded and (b) body-grounded configurations to eliminate the additional pressure on the surface of the face.

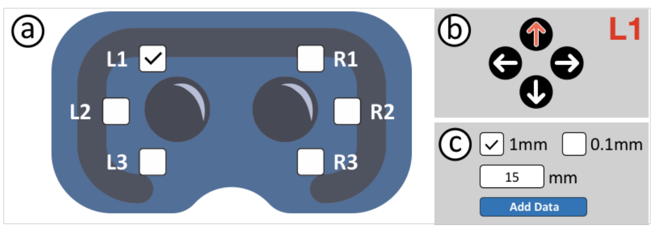

Figure 5. The control panel displayed in VR.

Procedures and Tasks

Participants were instructed to put on the Masque prototype while in a seated position. We used the pulley structure to cancel out the additional weight. In virtual reality, participants saw a control panel for the tactors and could manipulate it with a mouse and keyboard. As displayed in Figure 5a, there are six checkboxes on the panel, each of which represents a target tactor. After selecting a tactor, participants can further assign the stretch direction (Figure 5b). For each direction, the participants gradually adjusted the stretching distance to either 1mm or 0.1mm resolution, as shown in Figure 5c.

Participants were asked to use the control panel and report the maximum acceptable distances, *i.e.*, the maximum stretch distances they felt physically comfortable with; if the acceptable distance exceeded the capable moving distance of the tactor (*i.e.*, 15mm), the task stops and the acceptable distance will be recorded as 15mm. The orders of tactors and the subsequent order of stretch directions were randomly assigned to the participants. After all of the tactors were experienced, the experimenter displayed the participant's choices one at a time to ensure that no further changes were needed. At the end of the experiment, each participant received a semi-structured interview for participants and collected their preliminary feedback in regard to our device was collected.

Results

The overall results are displayed in Figure 6. Across all the conditions, the acceptable skin stretch distance was 14.85mm on average. Over half of the participants (9/12) reported a maximum distance of 15mm for all of the skin stretch conditions, which is also the maximum moving distance of our design. Although, participants did notice that applying long-distance skin stretches may change their vision or facial expressions, they considered that those skin stretches are *"acceptable and interesting if used for VR applications (P2, P5, P11)."* Thanks to the tactor design, no participant reported discomfort during the study. P1 and P5 said that *"it's like using a face massager and I am totally fine with that."*

For the other three participants reporting distances less than 15mm, the acceptable threshold among them is 14.22mm in average (SD = 1.58mm), among which, two participant reported maximum distances shorter than 14mm. They reported that *"when stretching upward too much, my fleshy cheeks were squeezed, which slightly interfered with my breathing (P3, P10)."* Their feedback informs us that future prototypes should also consider the facial anatomy of individuals.

This study's results help us to understand how to use Masque to create acceptable skin stretches for user studies and applications. To eliminate the possible discomfort during the study, in the following two psychophysical studies, we chose a 5mm skin stretch as the reference stimulus, and the minimum and maximum skin stretches were 0mm and 10mm, respectively. The 10mm skin stretch was considered acceptable by all of the participants in this study.

We then conducted two psychophysical studies seeking the answer for the following question: how well can participants discriminate (a) the distances and (b) the angles of skin stretch feedback? The two studies lead us to understand better participants' sensory limitations and can help us design skin stretch patterns used in VR applications.

DISCRIMINATION THRESHOLD FOR STRETCH DISTANCE

When developing applications for skin stretch feedback, designers need to consider the magnitude of the lateral skin deformation when developing applications for skin stretch

	Up	Down	Left	Right
L1	15 mm (SE:0mm)	15 mm (SE:0mm)	15 mm (SE:0mm)	14.75 mm (SE:0.25mm)
L2	15 mm (SE:0mm)	15 mm (SE:0mm)	14.61 mm (SE:0.23mm)	14.73 mm (SE:0.26mm)
L3	14.38 mm (SE:0.5mm)	14.6 mm (SE:0.4mm)	15 mm (SE:0mm)	14.3 mm (SE:0.66mm)
R1	14.71 mm (SE:0.28mm)	15 mm (SE:0mm)	15 mm (SE:0mm)	15 mm (SE:0mm)
R2	15 mm (SE:0mm)	14.98 mm (SE:0.01mm)	15 mm (SE:0mm)	14.78 mm (SE:0.21mm)
R3	14.56 mm (SE:0.35mm)	15 mm (SE:0mm)	15 mm (SE:0mm)	15 mm (SE:0mm)

Figure 6. The result of the comfort study.

feedback. This study's goal is to explore the discrimination threshold of the distances of skin stretches on the human face. As an initial exploration, this study focuses on two crucial factors of skin stretch : *Stretch Location* and *Stretch Direction*.

Regarding *Stretch Location*, we are interested in knowing whether the same amount of change is applicable for different locations on the face. Since the tissues of facial skin and the underlying muscles are complex, the sensitivity at different facial locations could well vary.

As for *Stretch Direction*, we are interested in knowing whether a certain change of the stretch is detectable in different directions. Given all possibilities, we chose the directions *Parallel* or *Perpendicular* to the natural skin movements induced by the facial muscles. This is because, given the anatomy of the face, the facial skin's surface covered by Masque usually moves inward or outward from the eyes. Taking the location R1 (Figure 7) as an example, when performing facial expressions, such as raising the eyebrows or blinking, the skin at R1 moves nearly vertically. In comparison, the horizontal skin movements at R1 (perpendicular movements), limited by the anatomy of facial muscles, are easier to be achieved by external forces. Considering this aspect of the face's anatomy, we assumed that the capabilities of sensing the two kinds of directions are unequal. Note that, also because of the face's anatomy, the natural skin movements of L2 and R2 are exactly orthogonal to the movements of the other four locations.

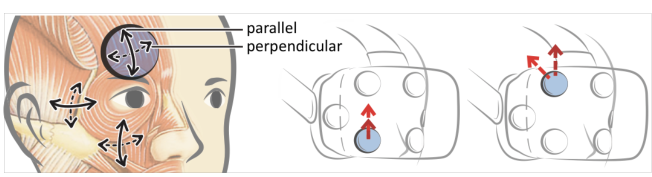

Figure 7. The facial anatomy around the HMD's facial interface. We examined the discrimination thresholds of stretch distances and stretch angles.

Stimuli Combination

We assumed that the skin's sensitivity at the symmetrical sample points (*i.e.*, , L1/R1, L2/R2, L3/R3) are similar. Therefore, participants were assigned three locations from each pair (*e.g.*, L1, R2, and R3).

There were two stretch directions, parallel and perpendicular. For points L1, R1, L3, and R3 in the parallel condition, half of the stretches were randomly chosen to point north and the remaining half pointed south. Similarly, in the perpendicular condition, half of the stretches were randomly chosen to the stretch east and the remaining half stretched west. In comparison, the stretch directions of L2 and R2 were exactly orthogonal to the other four positions. When displaying a stimulus, the tactor first stretches the skin to the destination at full speed (63mm/s), and then pauses for 1 second, and finally it moves back to its original position with a speed of 63mm/s. This process of displaying the stimulus was adopted based on referenced to previous works on skin stretch feedback [13].

Design

This experiment applies a 3×2 within subject factorial design. The independent variables are *Stretch Location* and *Stretch Direction* on the face. Six discrimination thresholds are found for these combinations.

This experiment uses a three-alternative forced-choice paradigm. Each combination consists of a series of blocks, in each block, three trials are presented, two with the reference stretch distance (S) and one with the test stretch distance ($S \pm \Delta S$). That is to say, the distance of a skin stretch for test trial was either longer or shorter than the reference trial by ΔS. Participants were asked to identify the test trial; the one which they felt was dissimilar from the others. The order of the test and reference trials was random for each block. For determining the value of ΔS, a one-up-two-down staircase procedure was used. The reference S was set to be 5 mm, as determined by the result of the comfort study. The step size of ΔS was initially set to 50% of the reference S. One incorrect answer increases ΔS. For the first three reversals, ΔS is decreased or increased 20% of the stretch distance, and by 4% for the remaining twelve reversals. The experiment finishes after six staircase runs are completed (3 locations and 2 directions). The order of the stair case runs was randomized among the participants. If the test stimuli exceeded the 10mm, the system considered it as a reversal and then proceeded with the staircase runs. However, such a situation did not occur during this study.

Procedures

At the beginning of the experiment, participants were instructed to sit and wear their Masque and the noise-canceling headphones. Like the previous studies, we utilized the pulley system to eliminate the additional weight caused from the skin stretch modules. In virtual reality, three buttons were displayed and used for the force-choice design. After experiencing the three stretches, the participants needed to press the appropriate numbered button using the VR controller to identify their choice. In general, participants conducted between 25 to 50 trials for each staircase while each staircase took between 10 to 15 minutes. Participants could take short breaks between the staircases.

Participants

Twelve participants (7 females and 5 males) between the ages of 20 and 26 took part in this study. Six of them had had experience using VR headsets and controllers. All of them have a normal sense of touch on the surface of their face and could easily wear on our prototype system. During the study, no participants reported feelings of discomfort.

Results

The average from the last 10 reversals was calculated for each participant. The estimated discrimination threshold of haptic force magnitude for each of the combinations was computed by averaging the thresholds of the participants. The estimated thresholds were then analyzed using a repeated measures ANOVA and Bonferroni corrected t-tests for pairwise comparisons.

Surprisingly, ANOVA yields no significant effect regarding *Stretch Location* ($F_{1.62,17.79}$ = .40, p = .635) and *Stretch Direction* ($F_{1.0,11.0}$ = 1.41, p = .261). The analyses shows also no significant interaction between the two variables ($F_{1.74,19.16}$ = 0.06, p = .924). The average thresholds across all conditions is 1.23mm (SD=0.46mm). These results suggests that the change in stretch distances must be at least 24.6% higher or lower than the current stretch distance to enable people to perceive a difference, and multiple levels of stretch feedback can be created by Masque prototype. For the directions not tested in this study, we assume the JND value remains similar, as the effect regarding directions was insignificant. Since the JND was not significantly affected by the locations and directions, designing skin stretch feedback becomes easier for developers. Note that, as the stretch distance increases, participants may become more sensitive to the changes as their facial expression is interfered with. Although further investigation is needed, we applied 30% JND value for our demo applications.

Direction	*L1/R1*	*L2/R2*	*L3/R3*
Parallel	1.21mm (24.2%) (SE:0.11mm)	1.29mm (25.9%) (SE:0.17mm)	1.32mm (26.4%) (SE:0.15mm)
Perpendicular	1.14mm (22.9%) (SE:0.11mm)	1.2mm (24.1%) (SE:0.12mm)	1.19mm (23.9%) (SE:0.11mm)

Figure 8. The average discrimination thresholds of stretch distances for each combination.

DISCRIMINATION THRESHOLD OF STRETCH ANGLE

Another important characteristic of skin stretch is the directional cues. Although, our prototype system supports 2-dimensional skin stretch, understanding the participants' capability for discriminating different angles of skin stretch on their face can help us to generate distinguishable directional cues.

Design and Procedure

The experiment applied a 3 × 2 within-subject factorial design. The independent variables are *Stretch Location* and *Stretch Direction*. Six discrimination thresholds are found for the combinations. We used the same reference distance and stretch speed as the previous study.

This experiment uses a three-alternative forced-choice paradigm. Each combination consists of a series of blocks, in each block, three trials are presented, two with the reference angle (S) and one with the test angle (S±ΔS). In the reference trial, the angle of S is the same as the *Stretch Direction* condition. The angle of test trial is either clockwise to or counter-clockwise to the reference trial by ΔS. The value of ΔS was determined adaptively. The order of tests and reference trials was random for each block.

The stimuli were similar to the previous study, where in the same *Stretch Direction* condition, half of the stretches of test trials are in the opposite direction to the other half. Except that, during the force choice, the stretch angle of the test trial (S±ΔS) follows the reference trial (S). That is to say, if the reference stimuli were randomly assigned to stretch to the north direction, the test trial also used a stretch to the north direction (within a range ±ΔS).

A one-up-two-down adaptive staircase procedure is used. The step size ΔS was initially set to 60°. One incorrect answer increases ΔS, and two consecutively correct responses decreases ΔS. For the first three reversals, ΔS is decreased or increased by 10°, and by 5° for the remaining twelve reversals. The experiment finishes after six staircase runs were completed. The order of the staircase runs was randomized among the participants. If the test stimuli exceeded the 90°, the system considered it as a reversal and then proceeded with the staircase runs. However, those circumstances did not occur during the study.

The procedures of this study are the same as those for the distance discrimination threshold study, except that participants are instructed to select the test angle from three trials. The participants are the same as in the previous study. In general, they conducted between 30 and 60 trials for each staircase, and each staircase took between 15 to 20 minutes.

Results

The discrimination thresholds of the stretch angles are displayed in Figure 9. The average from the last 10 reversals was calculated for each participant. The estimated discrimination threshold of stretch angle for each combination was computed by averaging the thresholds of participants.

We then conducted a repeated measures two-way ANOVA on the ratios with *Stretch Location* and *Stretch Direction* as independent variables. The analyses shows no significant interaction between the two variables ($F_{1.419,15.612}$ = 0.861, p = .406). The *Stretch Location* yields no significant difference ($F_{1.837,20.202}$ = 2.392, p = .120) These results indicates that the designer can utilize the same stretch angles on different facial locations and the perceived directional cue could be still valid. By comparison, the analysis shows that the *Stretch Direction* significantly affects the ratios ($F_{1,11}$ = 23.064, p <.005). The pairwise comparisons show that participants were more sensitive to *Parallel directions* than *Perpendicular* directions ($p < .005$). The average discrimination threshold of stretch angles across all conditions is 22.69°, and the highest JND value across the participants is 42°. The results suggest that participants could at least differentiate eight skin stretch directions on their face.

Direction	*L1/R1*	*L2/R2*	*L3/R3*
Parallel	21° (35%) (SE:1.7°)	20.04° (33.4%) (SE:1.77°)	19.41° (32.3%) (SE:2.84°)
Perpendicular	29.16° (48.6%) (SE:1.89°)	23.04° (38.4%) (SE:2.23°)	23.45° (39%) (SE:1.76°)

Figure 9. The average discrimination thresholds of stretch angles for each combination.

DEMO APPLICATIONS

We implemented three applications, all developed using the Unity3D game engine, and are integrated with the VIVE developing environment and tracking system. A set of profiles were created based on our previous study results.

Application 1: Motorcycle Racing

This application highlights the ability of Masque to simulate various characteristics of force feedback. Four profiles simulating the *weight*, *inertia*, *shakes*, and *normal pressure* from the helmet, are used according to the events in a motorcycle racing game, as displayed in Figure 10. Before the race, the user needs to put on a helmet. All tactors are actuated downward (3mm) to simulate the heaviness of the helmet. When the user is drifting on the racing track, in response to the directions of the drift, tactors L1/R1 and L3/R3 perform skin stretches in the opposite direction (between 6mm to 15mm), which creates a sensation where the helmet is pulled upon by inertia force. Also, the user receives constant up-and-down skin stretches on bumpy roads (5mm), simulating the shakes from the helmet. When the user passes through an acceleration board on the race track, the speed of the motorcycle will be boosted. In the mean time, tactors L2/R2 perform skin stretches outward from the eyes (between 6mm to 15mm), simulating a constant wind pressure on the face.

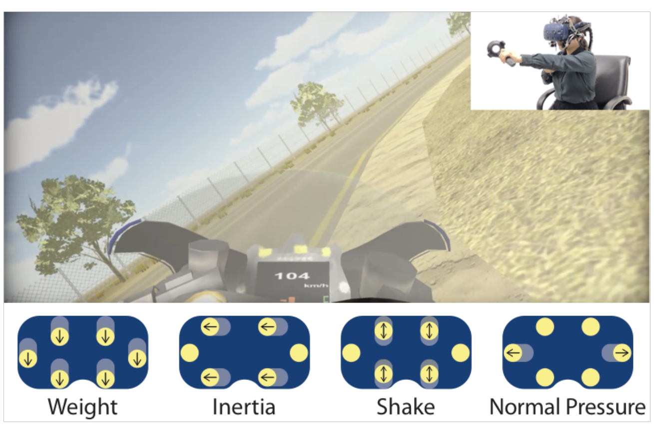

Figure 10. Motorcycle Racing.

Application 2: Snowball Fight

Interfering with users' movements in VR allows users to experience a weakened bodily state in regard to their VR character's "body". For example, Frozen Suit [1] creates a "freezing experience" by utilizing jamming patches to restrict the user's leg or arm movements. Inspired by their works, this application aims at exploring if adding restrictions on facial expressions can create valuable VR experience. Two profiles, *freezing* and *graze*, were created. In a virtual playground, the user needs to avoid the snowballs incoming to the face and try to throw snowballs at other players' faces (Figure 11). If the user's left eye gets hit, all left tactors constantly stretch inward (12mm), creating an restriction regarding opening the left eye. If the user barely avoids the attack, our prototype generates a short-term skin stretch to the eye corners (5mm), simulating the sensation of a graze from a snowball.

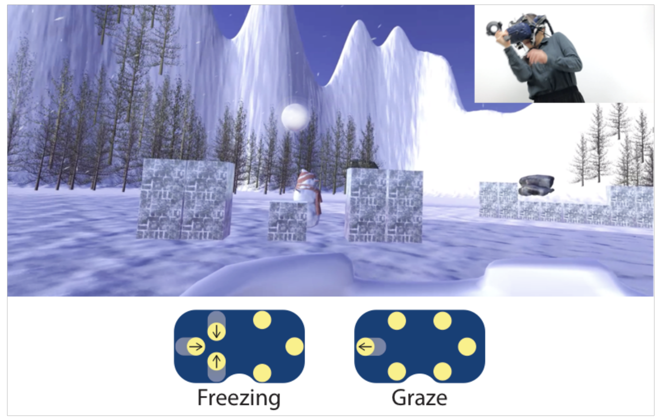

Figure 11. Snowball Fight.

Application 3: Virtual Museum Guidance

Our Virtual Museum Guidance app aims at demonstrating the Masque's potential for fine-grained directional guidance. In a virtual museum, the user is surrounded by valuable historical artifacts. A menu listing all of the artifacts is floating nearby the user. The user can select a desired artifact and starting to move toward the location of the artifact by following the directional cues (Figure 12).

We created skin stretch profiles for *looking up (8mm), down (8mm), to the left (12mm) and to the right (12mm)*. For these directional cues, we found that actuating multiple tactors toward the same direction creates better guidance experiences than actuating a singular tactors, as the user receives stronger haptic stimuli. We also designed a directional cue for *moving forward (12mm)*. We found that actuating tactors L2 and R2 when moved toward to the eyes simultaneously creates a directional cue to move forward.

A simple algorithm was implemented for finding the shortest path from the user's current position to the selected artifact. The Masque prototype generates the skin stretch profiles according to the directions of that path and the distance between the user and the destination. The algorithm sequentially generates the directional cues for the participants to look around or move forward. For *looking up, down, to the left, and to the right*, the tactors stretch to the same guidance direction and return to their original positions if the participant turns his or her head to the correct direction. Also, if the participants are close to the destination, the *moving forward* guidance will stop.

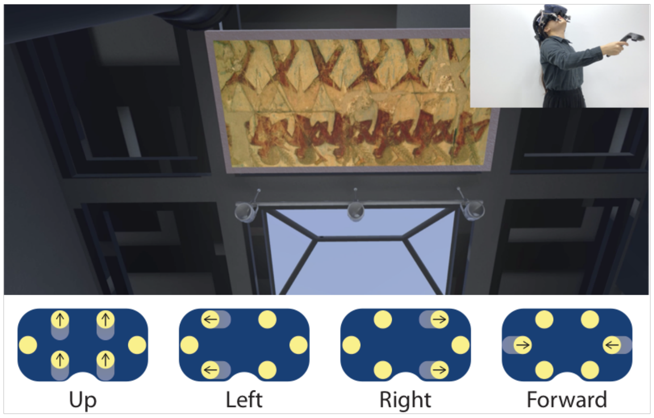

Figure 12. Virtual Museum Guidance.

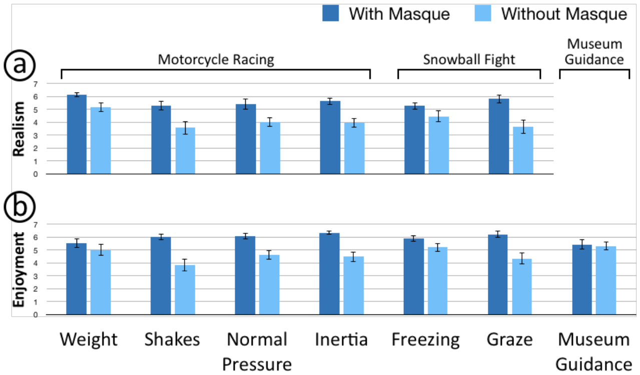

Figure 13. Agreement scores in regard to (a) Realism and (b) Enjoyment.

User Evaluation Study

To ensure that the skin stretch feedback generated by Masque is a valuable haptic addition to HMDs, we conducted a user evaluation study for the applications. This experiment is designed to measure the user's subjective feedback on Masque in comparison to use without haptic feedback. Participants were instructed to experience the three aforementioned applications one by one without time limitation. We recruited 12 participants (7 female and 5 male, aged from 22 to 26) for the study. Ten of them had had experience using VR headset and controllers.

The order of the applications was counter-balanced. For the haptic condition, participants were instructed to try every profile. For the no-haptic condition, participants needed to go through the same events without haptic feedback. The order of the haptic conditions was randomized. Note that, for Virtual Museum Guidance without haptic feedback, participants needs to look at the location of artifacts on a minimap nearby, that display the positions of the user, and the path to the target destination.

After this study, participants completed a questionnaire asking for agreement ratings on their feelings in regard to *Realism* and *Enjoyment* for each skin stretch profiles. Participants did not report the realism scores for Virtual Museum Guidance, as the profiles are not used to simulate the physical effects in virtual reality. Instead, we asked participants' overall enjoyment scores during the guidance. For example, in Snowball Fight, the participants were asked "*how realistic when your face hit by the snow?*" and "*how enjoyable the stimulus is in the fight?*" Ratings were made using a continuous numeric scale from 1 to 7, with 1 indicating "strongly disagree" and 7 "strongly agree." Decimal ratings such as 6.12 were permitted. The entire experiment took about 30 minutes.

Results and Discussion

The subjective ratings on realism and enjoyment were analyzed using a t-test.

Realism

Figure 13a displays the realism scores. For the Motorcycle Racing game, the t-test results indicates that all of the skin stretch profiles received significantly higher scores than the no-haptic condition (all $p < .05$). Most of them agreed that the skin stretches simulate well the perception of a physical activity when wearing the helmet. Three participants reported that "*it's like wearing an actual helmet (P6, P11, P12)!*" However, there were also two participants who gave lower scores to the *inertia* (3) and *shake* profiles (2.5), as they thought "*the force illusion is less realistic if there is no haptic feedback on the human body as well (P9, P10).*" Although body-scale feedback is beyond the scope of this paper, future designers should consider body-worn tactors for a more immersive experience.

For the Snowball Fight game, the t-test results indicates that compared to the no-haptic condition, the *freezing* profile received marginally-significant higher scores ($p = .057$) and the *graze* profile received significantly higher scores ($p < .01$). Half of the participants rated higher scores for the *freezing* profile, as they considered that the profiles "*can simulate the interference felt from the snow (P2, P6).*" However, the other half of the participants reported the *freezing* profile is less realistic as our system "*should provide thermal and vibration feedback after being attacked (P9, P11).*" Their feedback shows the importance of multimodal haptic feedback for VR interactions. In comparison, most of the participants agreed that the *graze* profile was realistic and helped them to revise head motions to doge virtual snowballs.

Enjoyment

As shown in Figure 13b, participants found applications more enjoyable with haptic feedback. For the Motorcycle Racing and Snowball Fight games, all of the skin stretch profiles received significantly higher scores than the no-haptic condition (all $p < .05$). All participants considered that skin stretches made the games more exciting and immersive. In the Snowball Fight game, three participants reported that "*the freezing and graze profiles shocked me and made me tense, therefore I became more aggressive and more competitive in this game (P6, P8, P12).*" Their feedback echoes previous works generating pain [22], showing that negative experiences may be as important as the positive ones.

Interestingly, Masque did not receive significantly higher enjoyment scores in Virtual Museum Guidance ($p = .27$). Although, all of the participants could distinguish the directions well and arrive at destinations without the help of visual clues, they also felt that the minimap should not be removed in the haptic condition. Four participants suggested that long-term skin stretches made them feel annoyed and they hoped that they could freely enable or disable the feedback. On the other hand, other participants considered that the skin stretches helped them to pay attention to the virtual environment instead of the minimap, making them feel more immersed during the guidance. Their feedback informs future designers to carefully design the long-term skin stretches and provide users the controllability in regard to haptic feedback.

DISCUSSION AND LIMITATIONS

We discuss insights gained, propose future research, and acknowledgement of the limitations of our work.

Limitations of Psychophysical and Application Studies

In this paper, we conducted two psychophysical studies by examining the factors of skin stretch distance and direction. While the results are limited by the two factors, we were able to apply the information learned when implementing demo applications. More factors will be examined in the future work, for example, combining skin stretch feedback with kinesthetic feedback, such as head and body movements, and examining if the discrimination thresholds will be effected. To enable more subtle skin stretch feedback, measuring the absolute threshold is needed.

The tactor movements in this study included only linear movements. An important research direction is to examine users' capability to discriminate *rotational* skin stretch. As rotational skin stretch has been found useful in inducing rotational limb movements [42], applying it to the face can be also used for motion guidance in virtual reality.

We conducted the psychophysical studies with the Masque device. Note that, owing to the facial geometry of individuals, the relative distances between tactors and facial features between participants could be varied. However, since the facial interface of HMDs is designed for the general population, the 30mm-sized tactors still covers the skin regions above, nearby, and below the eyes for ordinary users. The psychophysical study results were still examined using commercially-available HMDs. We believe this makes our results general to other existing head-mounted displays.

No HMD movement was observed during the JND studies. The HMD was worn firmly, and only one tactor was actuated for each JND value. When actuating one tactor, other tactors remained static and could be considered as a solid ground, which resists the actuated tactor and prevents the HMD from moving to opposite direction. However, when actuating multiple tactors, slight movements of the HMD were observed (measured by a Vicon tracking system, less than 1.5*mm* in average). Modifying the mechanical design to mitigate this issue is also considered as the future work.

Multimodal Haptic Feedback

To focus on skin stretch feedback, we excluded existing HMD outputs (*e.g.*, vibration or thermal feedback) in the experiments. Future work should examine how multimodal haptic feedback affects users' capabilities of sense as well as user experience. Recent works implement slip display on VR controllers for generating the perception of textures and found that participants welcomed that additional haptic feedback [25, 43]. For the HMD, slip feedback might be helpful, such as experiencing scratches on the face. However, the safety and comfort of users in regard to implementing other additional haptic feedback should be carefully examined.

Algorithms for Rendering Force Feedback

This study focuses on exploring the discrimination thresholds of the stretch distance and stretch direction. The profiles used for creating perceptions such as heaviness and inertia were pre-defined and customized by using the authoring tool. Like previous works exploring perception models on stiffness [31] for skin stretch feedback, to induce more realistic experiences, it is important to investigate the perception models on the face, which is also the next step of our work. Examining whether users really about the correctness of the stretch direction during the application is also an interesting future work as it could simplify the rendering algorithms.

Hardware Implementation

During the user evaluation study, two participants reported some tactor pairs did not equally fit their faces. This is because any given human face may not be perfectly symmetrical, and the tactor pairs were not applied to a symmetrical face. Subsequently we resolved this issue by adding to the thickness of the tactors manually so that the normal forces between the tactor pairs were the same. This is interesting and suggests that in order to match a user's facial geometry, the prototype should be able to be fine tuned in regard to the thickness and positions of shear tactors. We will revise the mechanical design of Masque to serve this purpose.

CONCLUSION

Our work introduces Masque, an HMD prototype that generates lateral skin stretch feedback on the surface of the face. With the Masque prototype, we conducted a comfort study to understand how to generate acceptable skin stretches through our prototype. The results suggested the distance threshold of skin stretch for the following studies and demo applications. The two psychophysical studies explore the discrimination thresholds of skin stretch distances and stretch directions. We implemented several skin stretch profiles based on the knowledge gained from these studies. Three VR applications were created to demonstrate the capabilities of the Masque prototype. In the user evaluation study, we examined the subjective ratings of the tested profiles. The results indicate that most of the participants regarded that the lateral skin stretches generated by Masque are valuable for enhancing the enjoyment and realism of their experience in VR. Future works will focus on exploring more factors for psychophysical studies, multimodal haptic feedback, and revising the mechanical design of our skin stretch modules.

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