Gaiters: Exploring Skin Stretch Feedback on the Legs for Enhancing Virtual Reality Experiences

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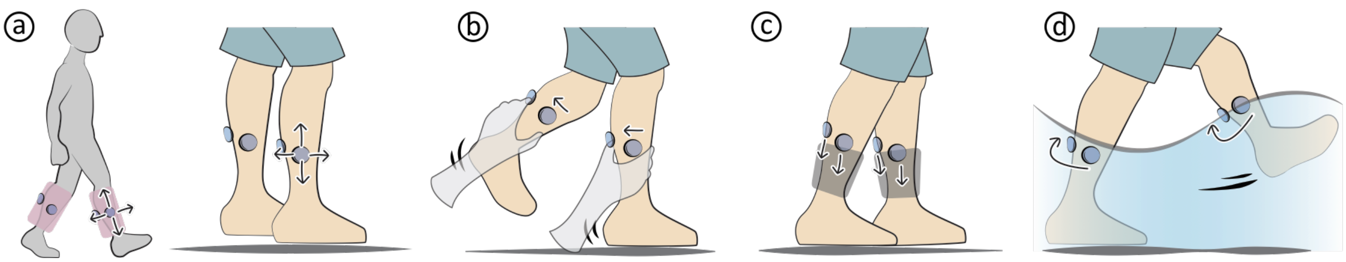

Figure 1. Gaiters are a pair of leg-worn devices where (a) each of which is integrated with three 2-DoF skin stretch modules. By generating skin stretch feedback, Gaiters can generate rich perceptions in VR, such as (b) a pulling force, (c) weight, or (d) a rotational force.

ABSTRACT
We propose generating two-dimensional skin stretch feedback on the user's legs. Skin stretch is useful cutaneous feedback to induce the perception of virtual textures and illusory forces and to deliver directional cues. This feedback has been applied to the head, body, and upper limbs to simulate rich physical properties in virtual reality (VR). However, how to expand the benefit of skin stretch feedback and apply it to the lower limbs, remains to be explored. Our first two psychophysical studies examined the minimum changes in skin stretch distance and stretch angle that are perceivable by participants. We then designed and implemented Gaiters, a pair of ungrounded, leg-worn devices, each of which is able to generate multiple two-dimensional skin stretches on skin of the user's leg. With Gaiters, we conducted an exploratory study to understand participants' experiences when coupling skin stretch patterns with various lower limb actions. The results indicate that rich haptic experiences can be created by our prototype. Finally, a user evaluation indicates that participants enjoyed the experiences when using Gaiters and considered skin stretch as compelling haptic feedback on the legs.

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INTRODUCTION
Haptic feedback helps users to link real world experience to virtual reality (VR) interactions. User evaluations of previous studies indicate that when combined with visual and audio information, haptic feedback makes VR applications more engaging and enjoyable. Although, utilizing vibrations is the most common approach for commercial haptic devices [50, 17], this method only engages a small range of sensations on the skin. To make the interaction more realistic, recent studies proposed haptic technologies that generate various sensory outputs, for example, thermal [46, 8, 51] and force feedback [1, 23, 6]. In addition, according to the users' activities,the aforementioned haptic feedback has been generated for stimulus to different points on the human body, including the head, finger, arm, and body torso [31, 27, 1, 44]. By comparison, the potential of haptic feedback for the lower body remains not fully exploited to date. We believe that adding haptic feedback to the lower body is equally essential for enhancing overall VR experiences.

In this paper, we propose generating skin stretch feedback on the human calf. Skin stretch feedback has been found as a promising approach to substitute sensations of textures [47], forces [41] and to deliver directional messages [55, 19, 20, 21]. More importantly, skin stretch, as cutaneous feedback, is more easily to be generated by compact mechanical wearable devices, making it especially suitable for VR applications that need larger workspace. However, how to leverage its benefits on the legs for VR interactions remains to be explored. In the first stage, we chose skin stretch by considering its compact implementation and the versatile perceptions it can induce. We decided to explore lower limbs as lower limb actions are crucial in (a) exploring environments and (b) interacting with physical objects. We conducted two psychophysical studies in regard to stretching the skin on the legs and examined the Just Noticeable Difference (JND) values. Two crucial factors, the location and direction of skin stretch, were considered for the studies. As it is known that skin stretch magnitude is related to the magnitude of illusory force (*e.g.*, lightweight or heavy) and the property of virtual textures (*e.g.*, for smooth or rough surfaces), we first explored the minimum change of skin stretch distance that is detectable by the participants. The results revealed an average JND of 16.85% across all the tested conditions. Furthermore, the JND values are affected by the skin stretch directions, where the participants exhibited more sensitivity to the vertical skin stretches. As for the discrimination threshold of the angles, the results indicates that on average, the participants could discriminate the directions of two skin stretches when the relative angle exceeds 14°.

We then implemented Gaiters, a pair of body-grounded, leg-worn skin stretch devices, where each of which consists of three shear contactors (or *tactors*). Each tactor is actuated by a pair of motors and can generate lateral skin stretches of different distances and at different angles. To help us better understand the potential of this hardware configuration, we conducted an exploratory study with Gaiters. We collected the participants' subjective feedback by asking them to perform different leg actions while experiencing premade stretch profiles. The results suggests that our device can induce rich haptic sensations for users. For example, when standing still, constant downward stretches made users feel heavy and weak, while leftward stretches evoked an experience of being guided by rotational forces. Finally, we developed two applications tailored for Gaiters to demonstrate its potential in VR. The users' experiences with these applications were used as the basis of a user evaluation. The study results showed that both Realism and Enjoyment were boosted, which makes us presume that Gaiters can also benefit related applications and regarded skin stretch as a valuable haptic feedback on the legs.

The primary contributions of our work are: (1) the concept of creating lateral skin displacement by physically stretching the skin of the user's legs; (2) the results of user studies that investigate the capabilities of skin stretch on the surface of legs; (3) the implementation of Gaiters, a proof-of-concept prototype; (4) an exploratory study testing the perceptions that can be induced by Gaiters; and (5) the applications that demonstrate our concept.

RELATED WORK

Virtual Reality Haptics on the Torso and Limbs

Recently, researchers have proposed generating haptics at different points on the body in VR, for example, generating textures and force sensations on the fingers by instrumenting VR controllers [37, 3, 59, 57, 13] or using wearable gloves [12, 11, 36]. To provide haptic feedback on the face, head-mounted displays (HMDs) were modulated to create wind [49], thermal sensations [51, 8], vibrations [45, 31], or normal force [6] feedback on the human face. User evaluations of these works indicated that the VR experience can be significantly enriched by adding haptic feedback. In this section, we focus on VR haptics applied to the human torso and limbs.

Grounded haptic devices are actuated mechanical structures with fixed bases in the environment and can generate strong and rich external forces. For example, Gruenbaum *et al.* proposed mounting a control panel on a robotic arm [22]. Actuating the panel generates force and torque feedback to help user control virtual widgets in VR. A pulley-based mechanical structure is also a promising approach. SPIDAR-H is a human-scale haptic interface utilizing a pulley system to produce pulling forces on the user's upper limbs [4]. Jeong *et al.* integrated a similar design with a CAVE environment to simulate the experiences of catching a ball [30]. Although effective, grounded haptic devices are stationary and bulky, which limits the user's workspace. Considering the need of portability and mobility, researchers have proposed various forms of wearable, body-grounded devices.

Use of vibration is a common approach for wearable VR devices, as the actuators are small-sized and lightweight. For example, Teslasuit is a commercial VR suit that generates vibrotactile feedback on the full body [50]. Similarly, previous works proposed attaching an array of vibrational tactors on the body and limbs [15, 27, 31, 14], which can produce spatial and temporal haptic feedback according to the VR contexts. Skin stretch feedback is also a promising approach to enhance VR experiences, which we discuss later in this section.

Electrical muscle stimulation (EMS) has also been applied to VR interactions. A typical EMS configuration involves multiple electrode pads and a signal generator. After placing the pads in close proximity to the human muscles, generating a signal to a pad elicits a muscle contraction, which can induce a user to perform certain motions or even actuate the user's body. For VR interactions, researchers have proposed generating EMS on the upper limbs to simulate the physical impacts [18, 38] from a virtual character or the weight [39, 40] of a virtual object.

Recently, using pneumatic interfaces is another potential solution for enriching VR experiences. Maimani proposes Frozen Suit, where a jamming system is implemented and used for constraining the user's joints [1]. Delazio *et al.* proposed integrating an array of pneumatic airbags in a jacket. By inflating or deflating the airbags, the user can feel constant normal forces across various body parts, which can be used to simulate a punch, push, or a moving snake [16].

In this paper, we focus on skin stretch feedback, a cutaneous feedback that has been extensively explored for use on the fingertips and the upper limbs.

Skin Stretch Feedback

When applying a shear force to the human skin, the force causes a lateral skin deformation and generates skin stretch feedback. Prior studies have shown that people are sensitive enough to detect such feedback [2]. As it is for cutaneous feedback, the design of a skin stretch device is usually simple and compact, making it especially suitable to be used for wearable interactions.

Compared to other cutaneous feedback (*e.g.*, vibration or normal pressure), users can further sense the directional cues of a skin stretch. Researchers have found that users can accurately recognize at least four directions of skin stretch on the fingertips [19]. Other researchers have proposed wearing skin stretch modules on the palm and the forearm for guidance or navigation applications. For example, Caswell *et al.* found that the human forearms are more sensitive to skin stretch directions than the palms, and proposed an arm-worn device that provides directional cues with a 2D shear tactor [5]. Directional cues can also be generated by combinational skin stretches. Chinello *et al.* propose augmenting four shear tactors around the wrist. By combining multiple 1D skin stretches, the wearer could perceive both translational or rotational cues [9].

Skin stretch has been found to be able to induce kinesthetic sensations, *i.e.*, skin stretch can induce illusory force perceptions. This makes skin stretch a promising approach for substituting force feedback in teleoperation or multimedia tasks. For example, Guinan *et al.* propose a handheld controller containing four shear tactors [24]. The device induces weight sensations when all the tactors slide to downwards, and can substitute inertia forces when tactors at opposite positions slide in opposite directions. With similar skin stretch patterns, Minamizawa *et al.* propose generating 1D skin stretches on the thumb and index fingers to simulate the weight and the inertia of a grasped virtual object [41]. With more complex mechanical design, the frictional forces and the stiffness [47, 48] of the grasped object can also be simulated.

Sato *et al.* have discovered the Hanger Reflex phenomenon [52]; When mounting a hanger on the head, the combination of normal and shear forces induces involuntary head rotation. Kon *et al.* has proposed a series of works that augment a hanger reflex device on the human ankle [34] and waist [33] for motion guidance applications. They also integrated the device with an HMD display for inducing the perception of being punched [32]. By comparison, Gaiters generates 2Dof skin stretches on the human calf and can be integrated with these existing efforts.

Recently, Horie *et al.* have proposed generating stretches on the skin of the buttocks skin stretch to induce an illusion of motion. The user evaluation indicates that users can sense different levels of acceleration when sitting on the device [26], showing the potential and feasibility of generating skin stretch feedback on the lower body parts.

Despite fruitful research findings and applications in regard to skin stretch feedback, recently works on generating skin stretch feedback on the legs mainly address lower-limb prosthesis users [7, 28, 29], where skin stretch is used as a message from the prosthesis during walking. How to apply skin stretch feedback on the legs for VR applications, remains to be explored. To initiate this research, we conducted two psychophysical studies and two user experience studies. An overview of our studies follows hereafter.

STUDY OVERVIEW

Several factors can be associated with haptic sensation, including the position of the skin stretch, the contact area between the tactor of the leg skin, and the limb movements during the skin stretch, etc. In regard to exploring skin stretches on the legs, we conducted two psychophysical studies and two user experience studies to answer the following questions: (a) how well can participants discriminate skin stretch distances and (b) skin stretch angles? In addition, as this feedback has been newly introduced to the participants, it is important to know that (c) when coupled with varied leg actions, what kind of haptic sensations can be induced by skin stretches? (d) Can the stimuli increase the realism and enjoyment in VR? The first two questions lead us to understand participants' sensory limitations. The last two questions help us to know how to utilize this feedback properly in VR.

DISCRIMINATION THRESHOLD OF STRETCH DISTANCE

When developing applications for skin stretch feedback, designers need to consider the magnitude of the skin deformation, in order to generate detectable minimum changes in skin stretch feedback. The aim of this study to explore the discrimination thresholds of users in regard to the distances of skin stretches made on the lower limbs. Considering the lower limb anatomy, we focus on two crucial factors of skin stretch: *Stretch Location* and *Stretch Direction*.

Regarding *Stretch Location*, since the tissues of the leg skin and the underlying muscles are complex, the sensitivity at different points on the leg locations could well vary. Considering the ease of wear, we decided to excluded the thighs and focus on the calves for this study. This is because, compared to the calves,the thighs are usually well-covered by clothes and are considered intimate to some users, which may cause additional configuration time or social discomfort. Also, a calf-worn prototype is easier to be worn or removed. Figure 2a illustrates the anatomy of the lower legs. Among many possible skin stretch locations on the calf, a previous study [7] finds that the human skin is more sensitive to the stimuli on the upper calcaneal tendon, the lower fibularis longus, and the soleus. We thus tested these three locations in the study.

Considering the symmetry of skin stretch positions, we also tried the front side of the calves. However, as less muscle is on the front of the leg, pressing tactors on the front size of the calves often causes discomfort. We eventually explored only the three locations on the two sides and the back of the calf.

As for *Stretch Direction*, we are interested in knowing whether a certain change of the stretch is detectable in different directions. Based on the anatomy of lower legs, we chose the directions *Vertical* or *Horizontal* for the lateral skin deformation caused by leg muscles, as illustrated in Figure 2b. This is because, given the anatomy of the leg, vertical muscle tensions are more natural and common than horizontal muscle tension. Thus, we did assume that the capabilities of sensing the two kinds of directions are unequal.

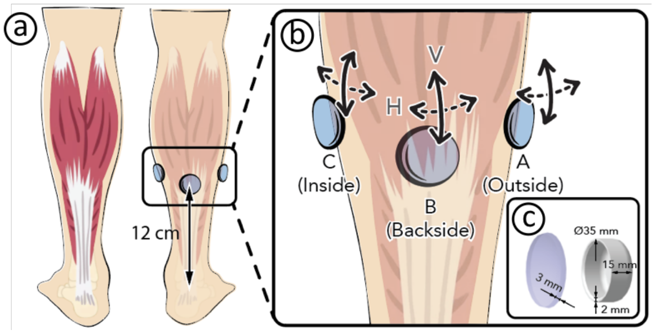

Figure 2. (a) The leg anatomy and the (b) stretch locations and directions tested in this study. (c)The shear tactor design.

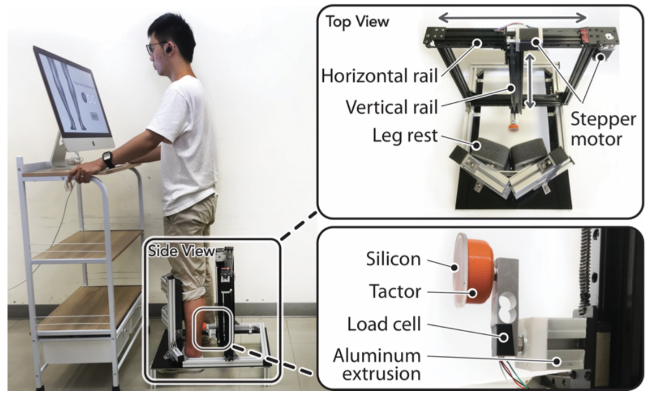

Figure 3. The apparatus for the psychophysical studies.

Apparatus

As illustrated in Figure 3, we implemented a leg-scale, grounded apparatus. The grounded configuration enables the apparatus to generate strong and clear forces without other ambiguous feedback.

The framework of the apparatus was assembled with railed aluminum extrusions. To generate skin stretches, we implemented two linear actuators with belt drives on the framework. Each belt is driven by a stepper motor with minimum displacement of 0.1mm, which enables smooth two-dimensional movements of the shear tactor. The tactor is affixed on the vertical linear actuator. A load cell sensor was placed between the rail system and the tactor. We asked the participants to adjust the apparatus until they thought the tactor was stable yet comfortable to attach. The average value from the sensor was approximately 14N across the participants. With 14N, the tactor could move smoothly without causing discomfort or slippage. Thus, we applied this force across the JND studies.

A leg rest (Figure 3) is built in front of the skin stretch device. We overlaid pieces of sponge on the rest to allow the participant to lean his/her leg on it comfortably. The rails allow the experimenter to easily reposition the skin stretch module according to the shape of the participant's legs.

Figure 2c illustrates the design of shear tactor. Since the curvature of skin surface varies across participants, we made the tactor as a hollow cylinder. This structure makes the tactor suitable for different curvatures of the calf and able to "trap" the skin inside the hollow, which can generate clear skin stretches without causing slippage. Moreover, the tactor is covered with a 3mm-thick silicon pad to ensure the user's comfort. To make sure the 3D-printed structure is strong enough, we set the thickness of the tactor at 2mm. After pilot tests, we decided to make the size of the tactor to be 35mm in diameter. This allows the tactor to generate clear lateral skin deformations without being affected by the curvature of any given user's calf.

Stimuli Combination

We assumed that the skin's sensitivity on both legs is similar likewise with each pair of sample points. Thus, for each participant, we randomly assigned one leg and examined the three sample points on the leg.

Two stretch directions, Vertical and Horizontal, were considered in the stimuli combination. In the Vertical condition, half of the stretches were randomly chosen to point north and the remaining half pointed south. In the Horizontal condition, half of the stretches were randomly chosen to point east and the remaining half pointed west. We applied a similar method in [20] to display a stimulus, where the tactor first stretches the skin to the destination at full speed, passes for 2 seconds, and moves back to its original position with the same speed.

Design

This experiment applies a 3×2 within subject factorial design. The independent variables are *Stretch Location* and *Stretch Direction* on the legs. Six discrimination thresholds were 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 results 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 10% of the stretch distance, and by 2% 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, we invited the participant to stand on our device in a comfortable way and guided the participant to lean his/her leg on the rest. We then adjusted the position of the tactor to match to location and pressure value.

According to our experiments, with a 14N normal force, users would not feel uncomfortable and no slippage would occur within the 10mm displacement. During the experiment, white noise was played through earphones to mask the audio cues produced by the motors. The interface of the JND study is displayed in Figure 4. Participants answered the force choices by using a mouse.

Figure 4. The interface of JND studies.

In general, participants conducted between 25 to 50 blocks for each staircase while each staircase took between 10 and 15 minutes. Participants could take short breaks between the staircases.

Participants

Twelve participants (6 females) between the ages of 20 and 26 took part in this study. Six of them had had experience using VR devices. All of them had a normal sense of touch on the surface of their legs 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 (Figure 5). The estimated thresholds were then analyzed using a repeated measures ANOVA and Bonferroni corrected t-tests for pairwise comparisons.

	A (outside)	**B** (backside)	**C** (inside)
Vertical	1.34mm (16.03%) (SE: 0.4mm)	1.17mm (14.05%) (SE: 0.33mm)	1.34mm (16.05%) (SE: 0.39mm)
Horizontal	1.55mm (18.6%) (SE: 0.49mm)	1.65mm (19.74%) (SE: 0.42mm)	1.38mm (16.6%) (SE: 0.38mm)

Figure 5. The average discrimination thresholds of stretch distances for each combination.

The JND values show that the change in stretch distances must be at least 14.05% higher or lower than the current stretch distance so that users can distinguish the difference, and multiple levels of magnitude can possibly be generated within a reasonable skin stretch range. We conducted a two-way repeated measured ANOVA analysis on JND values which indicates that there is a significant effect regarding *Stretch Direction* ($F_{1,11}$ = 18.7., $p < .001$). Further analyses indicate that on the outer position (A) and the rear position (B) of the calf, participants were more sensitive to vertical stretches than horizontal stretches. The result is inline with our assumptions considering the anatomy of the human calf. This is interesting, showing that skin stretches that follow the direction of natural muscle contractions are more detectable. The result also indicates that there is no significant effect regarding *Stretch Location* ($F_{1.99,21.89}$ = .44, p = .65), showing that the sensing capabilities of the three points of the calf are similar. Finally, no interaction was found between *Stretch Location* and *Stretch Direction* (p = .06).

DISCRIMINATION THRESHOLD OF STRETCH ANGLE

Previous works have shown skin stretches provide directional cues. These cues are useful for guidance [56], and limb rehabilitation [58] applications. This study aims to investigate the human's sensory limits in perceiving the differences between skin stretch angles on the legs. The results help us to generate distinguishable stretch directions.

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 also uses a three-alternative forced-choice paradigm (two references S and one test S$\pm\Delta$S). 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$\pm\Delta$S) follows the reference trial (S). That is to say, if the reference stimuli were randomly assigned to stretch to the south direction, the test trial also used a stretch to that direction (within a range $\pm\Delta$S).

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 12°, and by 3° for the remaining twelve reversals. The experiment finishes after six staircase runs are 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 were the same as in the previous study. In general, they conducted between 30 and 60 blocks for each staircase, and each staircase took between 15 and 20 minutes.

Results

The discrimination thresholds of the stretch angles are displayed in Figure 6. 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.

The average discrimination threshold of stretch angles across all conditions is 14°, and the highest JND values, across the participants, is 25.8°. The result suggests that it is possible for users to distinguish more than eight directions according to the skin stretch feedback on a single point of the leg.

We also conducted a repeated-measures two-way ANOVA analyses regarding the *Stretch Location* and *Stretch Direction* as independent variables.

Different from the trend of the first psychophysical study, the results indicate that there is no significant difference in both the *Stretch Location* ($F_{1.59,17.54}$ = 3.07, p = .081) and the *Stretch Direction* ($F_{1,11}$ = .52, p = .46), and there is no significant interaction between the two independent variables ($F_{1.69,18.53}$ = 1.68, p = .21). These results suggest that for distinguishing skin stretch angles, participants' sensing capabilities are not affected by the muscle anatomy of the calf.

	A (outside)	B (backside)	C (inside)
Vertical	13.1° (21.83%) (SE: 5.9°)	9.53° (15.88%) (SE: 3.76°)	13.43° (22.38%) (SE: 3.92°)
Horizontal	12.25° (20.42%) (SE: 4.07°)	11° (18.33%) (SE: 5°)	10.28° (17.13%) (SE: 6.32°)

Figure 6. The average discrimination thresholds of stretch angle for each combination.

PROTOTYPE IMPLEMENTATION

To demonstrate the novel interaction enabled by lateral skin stretch, we designed and implemented Gaiters, a pair of skin stretch devices worn on the user's calf. One Gaiter consists of three skin stretch modules. The shear tactor of each module is the same as those that we designed for the psychophysical study. When the user wears on Gaiters, the modules are in contact with the skin on the inner side, back, and outer side of the calf, respectively. As discussed previously, to avoid discomfort for the user, we did not apply any module to the front side of calf, which is less muscular.

Each module is in 80-mm square in shape and having a 45-mm thickness. A module contains a frame, an X-axis, a Y-axis and a tactor. As shown in Figure 7, the axes latch with the frame. When the gear motor actuates the rack on the Y-axis, the tactor and X-axis move toward Y direction along the rail, and vice versa. The origin of the tactor sits at the center of the frame, with maximum displacement of 10-mm in any direction. All parts of the module were 3D printed with PLA, with 10% filling to reduce the weight of the module. The tactor design is the same as was previously introduced for the psychophysical studies.

A module is actuated by 2 geared motors; one is used for the horizontal movements and the other for the vertical movements. 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 contact with the skin. The torque of the motors is 0.494N-m. A 38N normal force is needed to stop the tactor, which is enough to resist the normal force from the leg when wearing Gaiters The resolution of the tactor movements was 0.1 millimeter. We connected 6 motor drivers (TB6612FNG, SparkFun) to an Arduino Mega board that communicates with a computer via a USB port.

A challenge for our mechanical structure is that the shear tactors are also moved to the opposite direction from the skin stretch. This is because the human skin is a soft and multi-layer tissue. When actuating the tactor, the counter-force from the tactor also changes the position of the module itself. Our top priority was to prevent the counter forces from causing undesired tactor slippery or movements. To avoid the counter-force generated during stretching from affecting the user's perception, we integrated the modules on a calf brace (Figure 7). By this manner, the undesired counter-force is applied to the calf brace and evenly transmitted to the surrounding skin covered by the calf brace, which greatly mitigates the counter movements of the tactors.

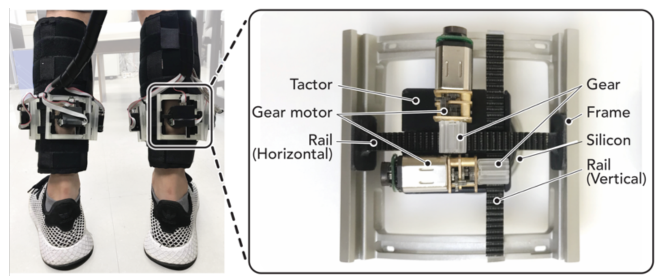

Figure 7. The mechanical structure of Gaiters.

EXPLORATORY STUDY ON INDUCED PERCEPTIONS

Prior works have shown that the combination of an action and a premade skin stretch profile can represent another perception. For example, generating a downward skin stretch when lifting up an object can induce the sensation of a weight [11, 54], or applying the same directional stretches around an arm to induce rotational forces [10]. The aim of this exploratory study is to test these action-coupled profiles and to understand how to utilize them to induce different types of perceptions.

Study Design

The action-coupled stretch profiles were designed based on two considerations, *Leg Action* and *Skin Stretch Profile*. The participants were asked to experience each premade stretch profile while performing an assigned action, and to report their experiences and agreements or lack thereof with the perceptions we evaluated in this study.

The perceptions evaluated in this study include *Pulling Force* [35, 48, 10], *Weight* [43, 41], *Rotational Force* [10], and *Friction* [47], as prior studies have shown that on the fingers or upper limbs, these perceptions can be induced by skin stretches. For Pulling Force, we asked participants if they felt that their limbs were being dragged in any direction. The definition of Weight is slightly different than Pulling Force, where participants needed to answer if their leg weight was increased, instead of being dragged by an external source. Rotational Force represents the sensation of unexpected rotational movements. Finally, Friction represents the sensation of a frictional force caused by an external object, which is more related to the tactile feedback on the skin instead of kinesthetic feedback.

Six stretch profiles were tested, including *Upward*, *Downward*, *Forward*, *Backward*, *Leftward*, *Rightward* profiles. For the Upward and Downward profiles, all shear tactors of Gaiters move upward or downward. For the Forward and Backward profiles, the tactors on the inner side and the outer side of the calf move to forward or backward simultaneously. As for the Leftward and Rightward profiles, all the tactors move to the leftward or rightward on both legs.

The stretch profiles were experienced when participants performed *Standing*, *Walking*, and *Kicking* actions. We considered these actions common and useful in VR games, and each of them involves different levels of body movements, respectively. For Standing and Walking actions, participants were asked to stand still or walk in place. The stretch profiles were fired on both legs. As for the Kicking action, participants were instructed to kick in the air by using their dominant foot, and only the dominant foot received the stretch profiles.

Prior research suggested that customizing the parameters of haptic feedback leads to a better haptic experience [16]. However, the aim of this study is to build an initial understanding of the perception of the action-coupled profiles. Thus, as a first step, we tested only the horizontal and vertical stretch profiles with the largest stretch distance that can be generated by Gaiters' tactors from their center positions (*i.e.*, 10mm).

Participants

Ten participants (7 females) between the ages of 23 and 30 were recruited in the study. Five of them were expert at developing VR applications, and three of the experts had had more than 2 years of experiences in developing VR haptic devices. All participants had had experience using commercial VR headsets and controllers. On average, each participant took 2 hours to complete the study.

Study Procedure

We first introduced the functionality of Gaiters to participants and instructed them to put on Gaiters. Participants were then asked to experience 18 action-coupled profiles (3 Leg Actions $\times$ 6 Skin Stretch Profiles). Each participant had to experience 6 profiles for each of the Leg Actions and then proceed to the next action. The order of Leg Actions was randomly assigned.

Participants were asked to wear a blindfold during the experience, so that they could focus on the haptic feedback. The experimenter was standing nearby to monitor the participants to ensure their safety. For each action-coupled profile, the stretches were fired at the moment when participants performed the leg action. Participants were allowed to experience the combination as many times as they wanted. We then showed the four perceptions to participants and asked them whether they agreed that the combination used effectively induced a specific perception by responding with a "Yes" or a "No." We used binary responses instead of a Likert scale, as that approach avoids tendency errors for a relatively long survey. Participants were also encouraged to report other perceptions they thought were related to the action-couple profile. The agreement rates are displayed in Figure 8. Hereafter, we discuss the insights gained from the agreement rates and participants' subjective feedback.

Results

To mitigate the noise from the brace, in the study, Gaiters actuated the tactors with longer distances (10mm). During the study, all participants reported that they could receive the stimuli well.

Pulling Force

As skin stretch contains the directional information, we assumed that all stretch profiles could be regarded as pulling forces. However, as shown in Figure 8, many action-coupled profiles receive agreement rates of less than 50%. The results suggest that future designers should carefully test their motion-coupled profiles to ensure the induced perception is acceptable.

As displayed in Figure 8, the agreement rates of $\{$Standing, Walking$\}$ $\times$ $\{$Downward, Backward$\}$ are higher than 70%. These results suggest that for Standing or Walking actions, generating Downward or Backward skin stretches can induce pulling sensations. When standing still, some participants felt someone was grabbing their legs when they received Downward or Backward stretches. *P1, P4,* and *P5* said "*it was somewhat spooky.*" The participants reported that their movements were "*slowed down (P5, P7)*" because the directions of Downward and Backward were perpendicular or the opposite of the leg movements during walking. Contrarily, the agreement rates for the Forward stretch were less than the rates for the Downward and Backward stretches. Based on our observations, a possible reason could be due to the calf's anatomy: The skin at the front side of the calf is less stretchable than the skin at the back. Thus, stretching Backward/Downward creates higher tension than stretching Forward and induces more significant sensations. Besides participants reported that they seldom experienced Forward stretches on their calves.

By comparison, the agreement rates for the Kicking action were all less than 50%. Participants reported that the perception of skin stretches were "twisted *(P7, P8, P10)*" by the perception of the muscle movements when kicking. They commented that the stimuli were "*more like an impact or an acceleration force instead of a pulling force (P2, P3, P9).*" This is interesting, showing that it is possible to induce versatile perceptions by action-coupled profiles. However, the feedback again suggests that the user experience should be carefully examined.

It is worth mentioning that, *P3* and *P9* answered "No" to all the combinations regarding pulling forces, as they expected both normal and lateral forces from a pulling force. Such a comment suggests that multimodal haptic feedback may be helpful to induce more realistic perceptions.

PULL

Stretch Pattern / Leg Action	Upward	Downward	Leftward	Rightward	Forward	Backward
Stand	30%	70%	30%	30%	30%	100%
Walk	50%	80%	10%	30%	50%	80%
Kick	50%	40%	40%	40%	50%	30%

WEIGHT

Stretch Pattern / Leg Action	Upward	Downward	Leftward	Rightward	Forward	Backward
Stand	70%	80%	20%	40%	30%	40%
Walk	70%	90%	40%	20%	40%	60%
Kick	60%	30%	50%	20%	30%	60%

ROTATIONAL FORCE

Stretch Pattern / Leg Action	Upward	Downward	Leftward	Rightward	Forward	Backward
Stand	20%	20%	80%	80%	40%	30%
Walk	30%	20%	60%	60%	20%	20%
Kick	30%	50%	40%	40%	30%	30%

FRICTIONAL FORCE

Stretch Pattern / Leg Action	Upward	Downward	Leftward	Rightward	Forward	Backward
Stand	100%	100%	100%	100%	80%	90%
Walk	90%	80%	90%	80%	100%	90%
Kick	80%	70%	90%	80%	100%	80%

Figure 8. The agreements of the four perceptions in the exploratory study.

Leg Weight

For the sensations of leg Weight, Figure 8 shows that when participants were standing or walking, generating Upward or Downward stretches induced a change in the perception of body weight. The participants reported that they felt their legs "*became heavier when receiving Downward stretches and felt lighter for Upward stretches (P2, P9, P10).*" The combination of Walking × Backward also received more than half of their votes of agreement. One participant reported that "*this combination can represent a pulling force or a weight perception (P2),*" showing that one action-coupled profile may be able to induce multiple perceptions.

Over half of the participants agreed that Kicking × {Upward, Backward} could represent a weight sensation. They felt that "*the Upward profile enhances the perception of leg weight movements (i.e., mass × acceleration)*" and "*the Backward profile strengthens the sensation of weight when I tried to kick forward (P1, P8, P10).*"

Rotational Force

For Rotational Forces, Figure 8 shows that when standing still, most of the participants can sense clear rotational forces from Leftward and Rightward skin stretches. These results also echos the results for the stretch profiles in previous works, where Leftward and Rightward stretches are used for motion guidance [34]. The participants who voted "YES" could also correctly translate the direction of the rotational forces.

By comparison, the agreement rates for {Walking, Kicking} × {Leftward, Rightward} are lower than those for Standing × {Leftward, Rightward}. Participants reported that "*the perception of rotational force became less significant when the leg action involves more muscle movements (P1, P7).*" These results shows that the mechanical design of Gaiters should be improved to generate stronger skin stretch feedback. We regard this as our future work.

Friction

Participants showed high rates of agreement on utilizing skin stretches to represent frictional forces. Every combination received agreement rates of no less than 70%. These results supports finding of previous works exploring skin stretch on the fingers [47, 53], showing that generating skin stretches on the legs can also simulate rich texture sensations from an object. Participants commented that the skin stretches can simulate "*water splashing(P1, P5, P6, P10),*" "*swimming fish grazing the legs(P4, P7, P10),*" "*crawling insects(P3, P6, P10),*" *and* "*swaying grass(P4, P6).*"

DEMO APPLICATIONS

We implemented two applications, all developed using the Unity3D game engine, and they were integrated with the HTC VIVE development environment and tracking system. To ensure users' mobility, we mounted the motor driver and the Arduino Mega board on a wide belt for users to wear. Two Vive trackers were mounted on the wearer's shoes. The system detects leg actions by calculating the acceleration speed of the trackers. A set of profiles were implemented based on our previous study results.

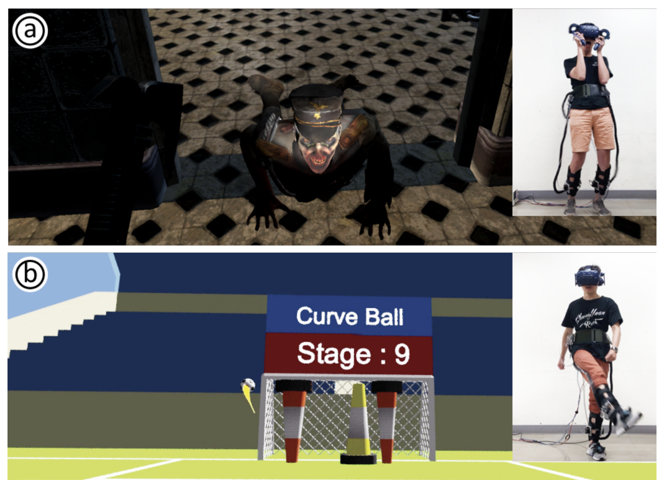

Figure 9. (a) Horror Escape Game (b) Fancy Goal Game.

Application 1: Horror Escape Game

We selected stretch profiles that were found effective in the exploratory study. Four profiles were used for *pulling force*, *grazed by something*, *weight*, and *water flow*.

In VR, the user needs to explore the environment in the dark and find a key in a basement to escape from an abandoned hospital. To get that key, the user needs to find an axe in the ward. On the way to the ward, the user may see zombies trying to grab their feet or mice passing by their feet. Simultaneously, our prototype generates skin stretches to simulate the feeling of being pulled (Walking × Backward) and grazed (Standing × Backward). After the user picks up the axe, they need to use it to destroy a block to get to the elevator. The elevator goes down to the flooded basement. When the user wades in water to find the key, the system generates Walking × Downward to simulate the increased resistance when lifting the legs. The user also may feel the direction of water flow by receiving Stand × {Leftward, Rightward} profiles. With the key, the user finally escapes from the hospital.

Application 2: Fancy Goal Game

From the exploratory study, we learned that when participants perform an intense leg action (*e.g.*, kicking), more perceptions can be induced. We believe it is important to utilize their feedback to showcase more interesting haptic experiences. Three profiles, Kicking × {Backward, Rightward/Leftward, Forward}, were implemented to simulate *impacts* and *acceleration forces*, per the perceptions reported by the participants in the exploratory study.

In VR, the player is wearing a fantasy goal-helping system to kick the soccer ball. We use 3 profiles for the 3 types of kicking action: normal shot, curve shot, and power shot. Each shot can be activated by a certain body posture. During the game, the player can see the visual feedback from the goal if the shot is activated correctly. The player needs to strategically choose the types of shot to get their scores.

When the player performs a normal shot, Gaiters generates the Kick × Backward profile to simulate the *frontal impact* from the ball. When the player performs a curve shot (activated by turning lower limbs by 45 degrees inward), Gaiters displays the Kick × {Rightward, Leftward} profiles to simulate the *side impact* from the ball. When the power shot is activated (by lifting the leg backward), Gaiters generates the Kick × Forward profile to simulate the *acceleration force* during the kicking action.

User Evaluation Study

We conducted a user evaluation to understand user's experiences while using Gaiters and to ensure that the skin stretch feedback generated by Gaiters is a valuable haptic addition. We recruited 12 participants (6 females, aged between 20 and 26) for the study. Each of the participants had had experience using VR; however, none of them had experience with leg-worn haptic devices.

We asked participants to experience the two applications respectively. The order of the applications was counter-balanced. There was no time limitation for the study and participants could experience the applications until they were satisfied. Participants were instructed to try every haptic condition in the applications. In the non-haptic condition, they need to experience the same events without haptic feedback. This condition is regarded as the comparison baseline for the applications.

After the VR experience, participants were asked to rate the sence of Realism and Enjoyment for each skin stretch profiles. For example, in Fancy Goal Game, the participants were asked *"how realistic was it when you kick the ball?"* and *"how enjoyable was the stimulus is in the game?"* Ratings were made using a continuous numeric scale from 1 to 7, with 1 indicating "strongly disagree" and 7 "strongly agree."

Results and Discussion

Figure 10 shows the realism and enjoyment scores which were analyzed using a t-test for two aforementioned applications.

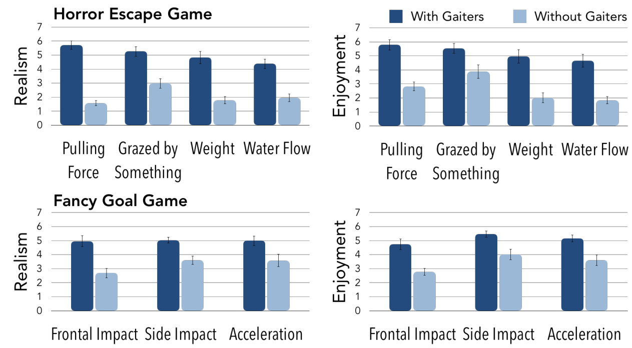

Figure 10. Agreement scores in regard to (a) Realism and (b) Enjoyment (Error bars show a standard error.)

Horror Escape Game

For realism, the t-test results indicate that all of the skin stretch profiles received significantly higher scores than the non-haptic condition (all $p<.05$). Three participants reported that the pulling sensation was "*realistic and helpful to understand the urgent situation (P5, P7, P8).*" By comparison, in the non-haptic condition, most of the participants felt that "*the visual or audio feedback was less noticeable when they felt scared or intense.*" One reported that "*without haptic feedback, I did not even know there was a zombie attacking me (P7).*" A VR developer commented that "*I think skin stretch is more realistic than vibration in this game, as the directional cues are in line with my real-life experience (P8).*"

There were three participants that gave lower scores ratings (less than 4) for weight and water flow profiles *(P3, P4, P12)*. Although they could recognize the profiles correctly, they thought "the area of skin stretch should cover both my legs completely as the water was above my knee." Their feedback suggests that the visual feedback should be designed by considering the size of shear tactors.

As for enjoyment, participants found the game more enjoyable in the haptic condition. All the action-coupled profiles received significantly higher scores than the non-haptic condition (all $p < .05$). All participants except *P9* considered that skin stretches made the games more scary and exciting. However, P9 rated lower scores to all profiles (2.0 on average), as she commented that "*the haptic feedback was distracting me from enjoying the visual atmosphere.*" This feedback suggests that VR applications should provide users with a controllability function in regard to haptic feedback.

Fancy Goal Game

For realism, the t-test results indicate that compared to the non-haptic condition, all skin stretch profiles received significantly higher scores (all $p < .05$). For enjoyment, the analyses also indicate that participants enjoyed the game more in the haptic condition (all $p < .05$).

Although, the average scores for realism and enjoyment were less than the scores for the Horror Escape Game, the results suggest that the action-coupled profiles can increase both the realism and enjoyment from *impact* and *acceleration force*. P3 explained that "*the directional cues from the legs help me* *to feel the path of the ball, which increased immersivity.*" One participant suggested that "*for the curve shot, the realism could be higher if the stretch distance (of Rightward and Leftward profiles) is larger (P6).*" This again suggests to us to modify the mechanical design of Gaiters in order to generate stronger skin stretch stimuli.

DISCUSSION AND FUTURE WORKS

Future Works on Studies

We conducted two psychophysical studies by considering two factors – skin stretch distance and direction. Although, the results are limited by the two factors, we were able to design skin stretch patterns based on the information learned. Our future work includes examining more factors, such as the size, shape, and stretching speed of shear tactors. Also, the JND values were examined under the standing condition. More body conditions, such as *Walking* and *Kicking* explored in the exploratory study should be tested in our future work as well. In the exploratory study, participants reported that leg actions effected their perceptions. This implies that the JND values might also be affected by leg actions.

Only four perceptions were voted upon in the exploratory study. However, the participants' feedback on kicking actions indicate that more interesting perceptions could be induced by Gaiters. Future work on this finding is to gather subjective feedback from more participants and to find out the mappings between various perceptions and action-coupled skin stretches, such as the perception of stiffness explored by previous finger-worn skin stretch modules [53].

Moreover, comparing perceptions generated by Gaiters with those from real-world events (e.g. actually having a user's foot pulled upon by someone) is interesting. It is inspiring as our future work. We firstly evaluated the non-haptic condition because our first aim was to make sure the stretch stimuli was usable on the calf.

Hardware Implementation of Gaiters

Participants' feedback in the exploratory study suggests that multimodal haptic feedback is a potential approach to generate more realistic perceptions (*e.g.*, normal pressure or vibration). Future work will focus on testing how multimodal haptic feedback affects users' sensing capabilities and what perceptions can be induced reliably.

To the best of our knowledge, Gaiters are the first wearable device that can generate 2DoF skin stretches on the human calf. However, owing to the mechanical structure and the number of motors, the weight and size of Gaiters are larger than other 1D skin stretch devices on the lower limbs [28]. Future work will focus on improving the hardware design and minimizing these two factors.

To keep the significance of the perception of rotational forces when walking or kicking, participants in the exploratory study suggested the generation of stronger skin stretch feedback. A prior study suggests that the stretch stimuli can be enhanced by increasing the stretch distance or speed [25]. However, this is a trade-off, as increasing both factors also increases the chance of causing undesired skin slippage. A possible solution is to use multimodal feedback to enhance the magnitude of the stimuli. Further investigation regarding this trade-off is needed.

Previous work suggests that to prevent undesired skin slippage, the curvature of the tactor should be determined by considering the hardness of the skin, which means the tactor size on the left and right side of the calf should be larger than the back [42]. We will apply this design in our future implementation.

Other Potential Applications

For the discrimination thresholds, we found both distance and angle JND on the calf are larger than the values for the fingers, palms, or forearms [9, 24, 43, 47, 54], even though we adopt larger normal force and size of shear tactors on calf. The result echoes previous psychophysical studies indicating the sensitivity of lower limbs is less than the fingers and upper body parts [9, 24]. and participants could distinguish more than 8 directions. This suggests more potential applications other than VR applications. For example, notifying the user's leg movements in a dance training system, or guiding the user to perform limb rehabilitation.

It would be also interesting to place the skin stretch devices at different points on the body, including the torso. As a full-body haptic suit has become more and more popular, we believe that skin stretch feedback, as a cutaneous feedback, is suitable to be implemented via the suit and can further increase the depth of VR experiences.

CONCLUSION

This paper introduces Gaiters, a pair of skin stretch devices on the skin of the lower limbs. In order to understand the benefits of skin stretch feedback, we first first conducted two psychophysical studies for exploring the discrimination thresholds of skin stretch distances and stretch directions. The results suggest that participants could discriminate two stretch distances when the difference between them exceeds 16.85%. As for the skin stretch angles, participants could distinguish the directions of two stretches if the relative stretching angle was larger than 14°. We implemented the Gaiters, a pair of skin stretch devices that can generate 2-DoF skin stretches on the user's lower limbs. An exploratory study helped us to understand how to apply varied skin stretch profiles to induce a certain type of illusory force. The gained insights were applied in two VR applications that we created for demonstrating the capabilities of Gaiters. In the user evaluation study, we examined the subjective ratings of the tested stretch profiles. The results indicate that most of the participants regarded our system as a useful device to increase the realism and enjoyment of the applications. Future works will focus on exploring more factors for psychophysical studies, realizing multimodal haptic feedback on Gaiters and improving the mechanical design of our skin stretch modules.

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