Perception of Skin Stretch Applied to Palm: Effects of Speed and Displacement

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Abstract. Skin stretch is a powerful haptic effect with a great potential as a feedback mechanism for digital gaming applications. For example, it has been shown to communicate directional information accurately to game players. However, the existing devices apply stretch to the tip of index finger except the Reactive Grip game controller by Tactical Haptics, which applies skin stretch to a user's palm and finger pads. We have designed a compact hand-held haptic device that applies skin stretch to the palm via an actuated tactor. Compared to the fingertip, the palm is slightly less sensitive to skin stretch but affords larger stretch area. The stretch area of the palm enables us to control both tactor displacement and speeds for a broader range, resulting in richer haptic feedback. Using this device, we conduct experiments with 8 participants to investigate the effects of tactor displacement, speed, direction and hand orientation on perceived magnitude of skin stretch. The results of the study show that not only the tactor displacement but also the speed has a significant effect on the perceived intensity of skin stretch and the mapping function between them is nonlinear. Moreover, it appears that the tactile sensitivity of human palm to skin stretch is not homogeneous and stretch applied to the radial aspect of palm (towards the thumb) results in higher intensity than that of ulnar aspect.

Keywords: Haptics · Gaming · Tactile feedback · Skin stretch · Palm

1 Introduction

The gaming industry is one of the fastest growing industries, reaching a $91.5 billion US dollar market worldwide value with 9.4 % growth rate in 2015 [14]. Great effort is paid to enhance the gaming experience of users by the industry. Research shows that multi-modal stimuli significantly augments user experience and engagement in digital gaming [15]. In this regard, researchers have already exploited the visual and auditory channels, but relatively little attention has been paid to the haptic channel. However, this may change in time with the recent progress in tactile haptics leading to more compact and low-cost interfaces that stimulate our fingertip and/or palm in new ways.

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For example, *skin stretch* is a new form of tactile feedback that has a great potential in displaying directional information and has recently been implemented in gaming applications [1, 8, 9, 17, 18]. Skin stretch feedback simulates the skin deformation as it happens when our extremities are in tactile interaction with the real objects. For this purpose, skin is deformed by moving a tactor (pin), which is in contact with the skin, in the tangential direction. Bark et al. show that skin stretch is superior to vibrational feedback, which is the most common haptic feedback in the gaming industry, on communicating directional cues [2]. Moreover, it is suggested that skin stretch can convey sensory substituted force information better than traditional audiovisual feedback [19, 20]. Arasan et al. convey rotational direction via skin stretch applied to a finger holding an active stylus that is embedded with a DC motor [1].

Skin stretch has been investigated in the forearm, foot, palm, and fingers [2–4, 6, 7, 12, 16]. In the context of this paper, we focus on the skin stretch applied to palm and fingers. In fact, the earlier research on tangential skin stretch has primarily focused on fingertips. Paré et al. [16] conduct magnitude estimation experiments with 7 participants for tangential and normal skin deformation applied to fingertip. The participants are asked to assign values for the stimulus intensity varying from 0.15 N to 0.64 N under 3 different loading rates (0.1, 0.2, 0.3 N/s). Their results show that perceived stretch intensity is in a linear relationship with the applied force magnitude regardless of the rate and direction. Gleeson et al. explore the effects of displacement, speed and movement direction of the tactor on identifying the direction of stretch applied to fingertip [6]. The authors have conducted a user study with 11 participants. The participants are asked to identify the direction of stretch (north, south, west, east) for the tactor displacements varying from 0.05 mm to 1 mm at speeds varying from 0.5 mm/s to 4 mm/s. The results show that (a) participants identified the directional cues with almost 100 % accuracy for 1 mm displacement, (b) an increase in tactor speed, up to 4 mm/s, significantly improves the perception of direction, (c) direction of the cue also affects the accuracy.

A number of studies investigating the skin stretch or shear applied to palm [5, 10, 11] are much less than those of the fingertips. Moreover, to our knowledge, all of these studies are in the area of neuroscience and have focused on identifying the mechanoreceptor locations and recording their action potentials rather than human tactile perception. Johansson and Vallbo conducted experiments with 40 healthy adults to determine locations and distribution of low-threshold mechanoreceptors in human hand via recording impulses from median nerve during von Frey hair indentation [11]. They derived the density map of each type of mechanoreceptors (FAI, FAII, SAI, SAII) in hand (see Fig. 1). Edin et al. conducted a 4-month long experiment with 14 participants. In the experiments, they recorded mechanoreceptor response data from the right median, right radial, right inferior alveolar and left inferior alveolar nerves during skin stretch stimuli that are applied with 3 different brushes. Their results show that the mechanoreceptor response to skin stretch depends on the stimulus displacement, speed, and direction [5].

Compared to the fingertip, the palm is less sensitive to skin stretch but affords larger stimulation area. Since biomechanics research shows that human skin displays strain-dependent and rate-dependent viscoelastic behavior [2], having a broader range of tactor displacement and speed can potentially lead to richer haptic effects. In this study, we have investigated the effect of tactor speed, displacement, direction and hand

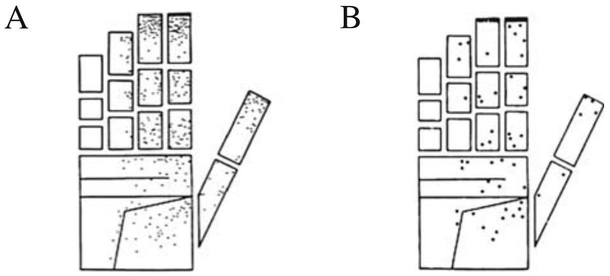

Fig. 1. A. Receptive fields in a human hand, B. Locations of SAII receptors, which are highly sensitive to lateral skin stretch and directional information, in human hand [10, 11].

orientation on the perceived magnitude of skin stretch applied to the palm. For this purpose, we have designed a compact, hand-held haptic interface that stretches the skin of the palm for tactile feedback and conducted magnitude estimation experiments with 8 participants under two different grasp orientations (horizontal and vertical) of the device.

2 Device Design

We have developed a compact, cable-driven, and hand-held haptic device that stretches palm skin with a tactor having one degree of freedom movement capability. The device is originally designed to provide independent tactile feedback to the fingers and palm simultaneously via 2 tactors separated by 180°. The device is made of two symmetrical half cylinders; each can house a motor and a cable-driven mechanism with a moving tactor for applying skin stretch to the palm and the fingers independently (see Fig. 2).

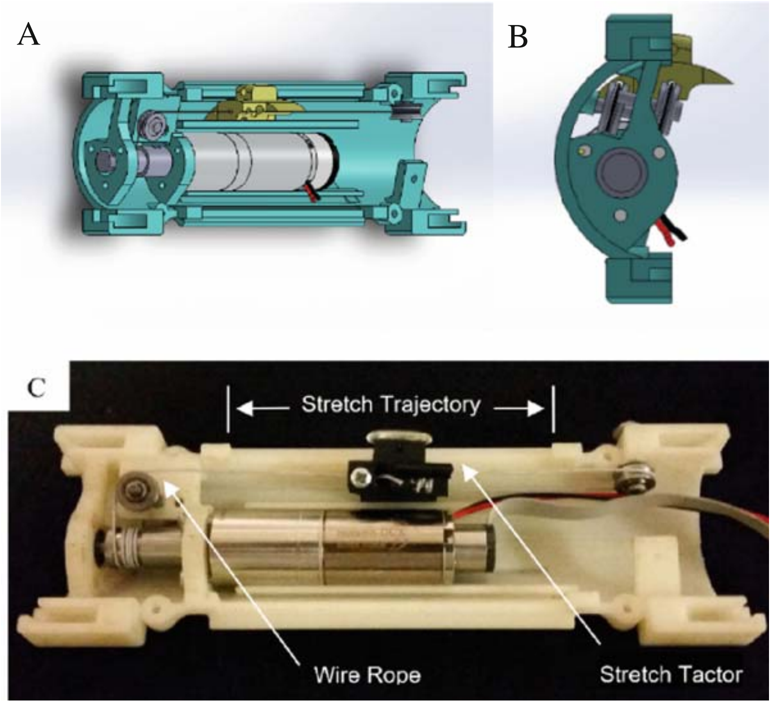

Fig. 2. A. and B. CAD model of the hand-held haptic device enabling skin stretch to palm. C. Realization of the design

However, at the time of this study, only the part applying stretch to the palm has been implemented. When assembled, the device has a diameter of 36 mm and is suitable to grip by an average person. The cylinders and the tactor are 3D-printed (uPrint SE, Stratasys). The top surface of the tactor is a half ellipsoid for smoother tactile interaction (width: 14 mm, depth: 7 mm and height: 1 mm, surface area: 86 mm^2) and made of silicone rubber for a more natural tactile feel. The tactor has a total travel range of 64 mm. The power is transmitted to the tactor from a DC motor (DCX16S EB KL 6 V, Maxon) via a coated steel wire rope of 0.5 mm thickness and three pulleys. The rotational speed of the motor and the resulting trajectory of the tactor are controlled by Maxon EPOS2 24/2 Positioning Controllers. The actuation system is capable of reaching a maximum speed of 68 mm/s with an acceleration of 38 mm/ms^2 and positional resolution of 0.05 mm under no-load conditions. In our design, we have targeted to reach relatively larger displacements with higher tactor velocities compared to earlier on fingertip [6, 9, 16]. Our aim is to take advantage of a relatively larger area of the palm for investigating the interplay between displacement and speed to augment the perceived intensity of skin stretch.

3 Experiment

We have designed a magnitude estimation experiment (as in [16, 21]) to investigate the effect of tactor displacement, speed, direction, and hand orientation (orientation of the grasped haptic device) on perceived magnitude of stretch applied to the palm.

3.1 Participants

8 volunteers (seven males, one female; the average 26.2 ± 2 years) participated in the experiment. All participants are right-handed with no known sensorimotor problems.

3.2 Stimuli

A stretch stimulus is a combination of 4 different tactor displacements (2, 4, 8 and 16 mm), 5 different tactor velocities (4, 8, 16, 32 and 64 mm/s), 2 different movement directions of the tactor with respect to the palm (radial, towards thumb and ulnar, away from thumb), and 2 different device orientations (horizontal and vertical). A total of 320 stimuli (5 displacements × 4 velocities × 2 directions × 2 holding orientations × 4 repetitions) is applied to the right palm of the participants in two sessions. Each stimulus is a half stroke of the tactor (one-way movement). During each stimulus, the tactor starts its movement from the center position (the midpoint of the travel range) and terminates after the desired displacement has achieved. It follows a trapezoidal velocity profile in which the acceleration and deceleration periods are much shorter than the total travel time. After the desired position is reached and the subject enters her/his response to perceived magnitude and direction, the tactor is moved back to the center position with a speed of 40 mm/s.

3.3 Experimental Procedure

Before the experiment starts, the participants are informed about the nature of the experiments and the experimental procedures. They are instructed to sit on a chair in front of the experimental setup, which includes the skin stretch device mounted on a fixture (see Fig. 3). This fixture ensures horizontal and vertical holding orientations for the device. Participants are asked to grasp the device with a certain amount of force in a comfortable manner. The grasp force applied by the participants is not recorded and adjusted manually during the demonstration session by trial and error such that the participants could feel the stimuli comfortably. Participants are asked to apply same grasp force across the trials, but obviously each may apply a different amount of force individually due to the difference in her or his tactile sensitivity levels. We eliminate possible variances in perceived magnitude due to grasp force and individual sensitivity levels via normalizing data across participants in our analysis. During the experiments, participants are asked to wear headphones playing white noise to block the noise coming from the motor. They are also provided with a soft pad to place their elbow to reduce fatigue. Before the actual experiments, the participants are presented with a training session displaying all possible combinations of the stimuli once in the vertical orientation of the device (40 stimuli). During the experiments, the participants are asked to estimate the direction of the stimuli (left/right and up/down for the horizontal and vertical orientations respectively) and its stretch magnitude. They are allowed to enter any positive number up to four digits for the magnitude. The participants enter their responses using a small keypad and their left hand. The stimuli are displayed to the participants in random order while the same order is used for each subject. The experiments are completed in two sessions, each taking approximately 30 min.

Fig. 3. Experiment setup

3.4 Results

The participants have successfully identified the direction of the tactor movement with a high accuracy of 98.12 % ± 1 %. The minimum accuracy in identifying the direction (93.75 % ± 6 %) was observed for stretch stimuli with 2 mm displacement at 4 mm/s speed in the ulnar direction.

We applied a normalization to the magnitude data based on the method suggested by Murray et al. [13]. For this purpose, we first computed the geometric mean of all responses, MG, and then the geometric mean of each subject, MG_P. Finally, the normalized value for each subject is calculated by MG/MG_P.

We applied 4-way ANOVA analysis to investigate the effect of tactor displacement, speed, direction, and holding orientation of the device on normalized skin stretch magnitude. The analysis shows that holding orientation has no significant effect on magnitude (hence, the data collected from the vertical and horizontal device orientations can be merged). Then, we combined participant data from both orientation conditions and calculated mean intensity values across trials for each participant. And, we apply 3-way repeated measures ANOVA analysis using [23]. As expected, speed ($F_{4,28} = 15.301$, $p < 0.0001$) and displacement ($F_{3,21} = 43.566$, $p < 0.0001$) have significant effects on the stretch intensity. Unexpectedly, stretch direction also has a significant effect on the perceived intensity ($F_{1,7} = 17.295$, $p < 0.005$). Our results also show that there is an interaction effect between displacement and speed ($F_{12,84} = 4.268$, $p < 0.0001$) and direction ($F_{3,21} = 8.761$, $p < 0.001$).

ANOVA analysis showed that stretch intensity is a function of speed and displacement and it also shows that interaction between speed and displacement is significant. In the light of this information, we fit a first order model to the averaged intensity data across participants (Eq. 1). The R^2 values of the fit functions are 0.994 and 0.989 for radial and ulnar directions, respectively (see Table 1 for the coefficients). Statistical analysis shows that all coefficients of the model are significant.

$$\mathrm{I}(v, x) = \mathrm{A}x + \mathrm{B}v + \mathrm{C}xv + \mathrm{D} \tag{1}$$

In the equation, I is the perceived stretch magnitude while x and v represent the displacement and speed of the tactor, respectively.

Table 1. The coefficients of the fit function.

	A	B	C	D
I_{Radial}	0.37	0.016	0.0033	1.26
I_{Ulnar}	0.26	0.0096	0.0034	1.40

3.5 Discussion

In the experiment, 16 mm is the longest displacement condition. Stimuli with 16 mm displacement, applies stretch and some slip together to the palm. The earlier research showed that slip has no adverse effect on movement direction estimation [22]. Moreover, the same study also shows that humans could not detect slip applied to fingertips

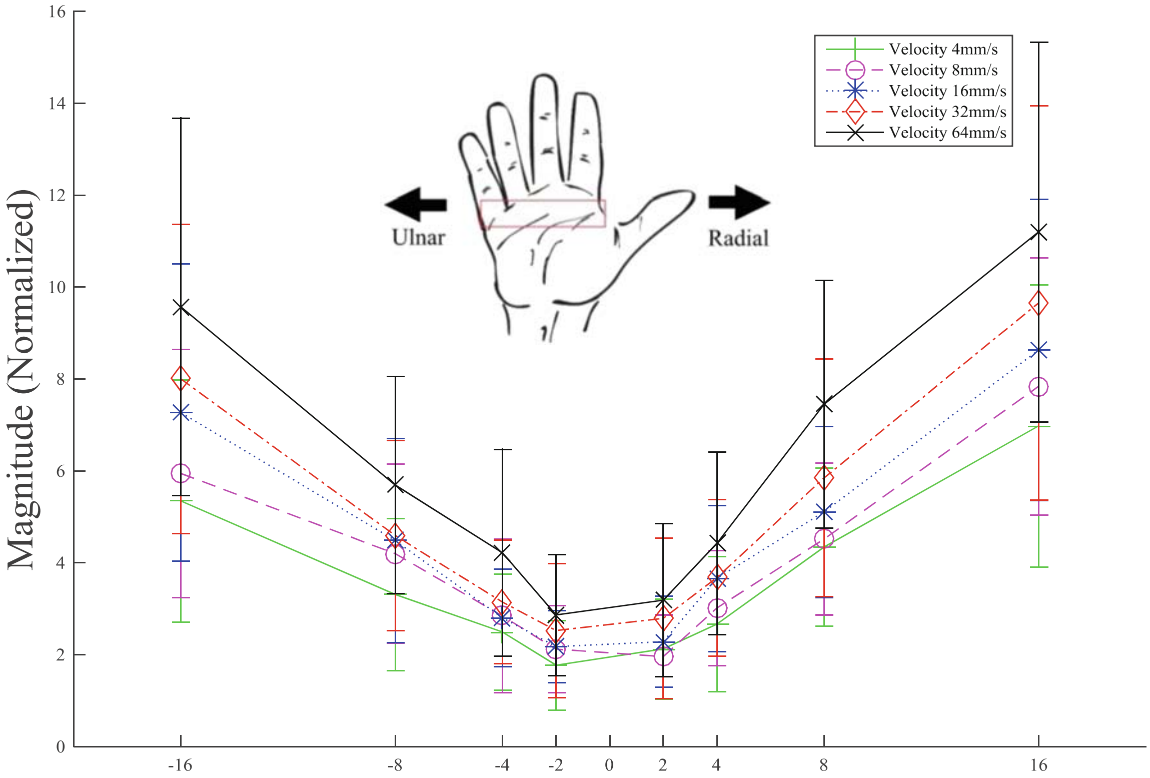

Fig. 4. Perceived stretch intensity as a function of tactor displacement and speed. (Color figure online)

by a smooth surface that is displaced for 14 mm. In the light of this information, we do not believe that slip has a significant effect on our results since our tactor has a smooth surface and palm is less sensitive than fingertips.

Figure 4 shows that an increase in the tactor speed results in an increase in the perceived stretch magnitude in movement directions, left and right, on the palm. The earlier neuroscience studies performed on human palm [5, 24] supports our finding. On the other hand, [16] who suggests that speed has no effect on the perceived stretch magnitude does not agree our finding on the effect of movement speed on perceived stretch magnitude. However, the rate of loading in [16] was quite low, so it is not surprising that they did not observe this effect, as is observed herein for the palm and previously for fingertips [13]. Furthermore, it appears that the relation between perceived magnitude and the tactor displacement and speed are nonlinear (see Eq. 1).

Finally, it appears that tactile sensitivity of the human palm to skin stretch is not homogeneous and stretch applied to the radial aspect of palm (towards thumb, up) results in higher intensity than that of ulnar aspect (away from the thumb, down). It is known that mechanoreceptors are not distributed uniformly in the palm. In general, there are more receptors (see Fig. 1A), in particular, more SAII receptors (see Fig. 1B) in the radial direction. Also, the topography of the palm could be another reason for asymmetry in skin stretch perception. In the radial direction, the index finger's metacarpophalangeal joint creates bump towards the palm, which increases pressure on the tactor on this region. For this reason, we present the data for the radial and ulnar stimuli in two separate plots for perceived stretch magnitude (see Fig. 5). In these plots, perceived stretch magnitude of the participants is presented as a function of both

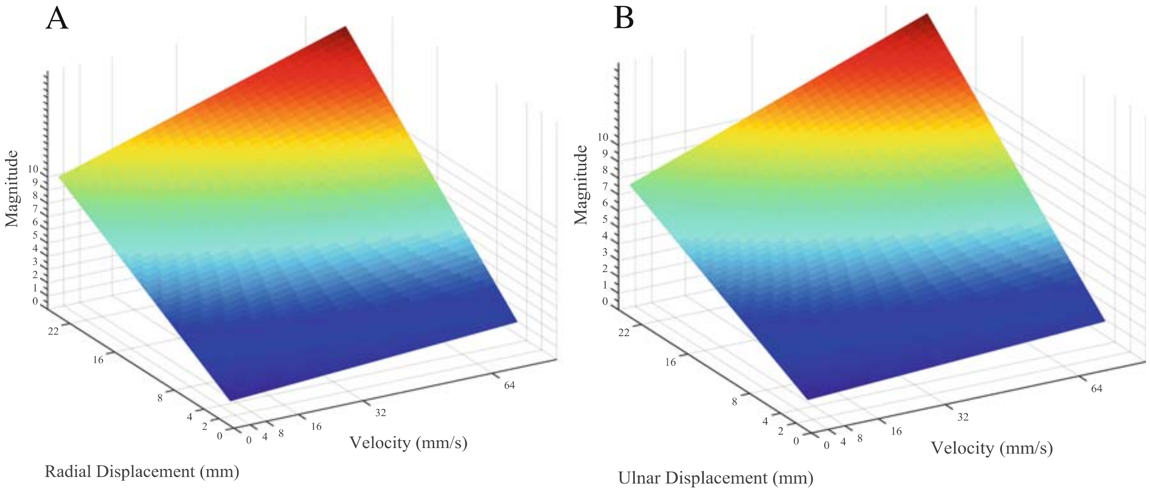

Fig. 5. Perceived stretch intensity as a function of tactor displacement and speed based on a surface fit using Eq. (1) to our experiment data: A. Lower perceived magnitudes observed for ulnar direction (away from the thumb, down). B. Higher perceived magnitudes observed for radial direction (towards thumb, up). See ulnar/radial diagram in Fig. 4.

displacement and speed. Moreover, a first order equation has been shown as a fit model for perceived skin stretch intensity in terms of tactor displacement and speed. Color coding is used to display iso-regions of the same perceived magnitude. As observed from these plots, the same haptic effect via stretch can be obtained by the combinations of different tactor displacement and speeds. For example, in the radial direction, a stretch intensity perceived by 10 mm displacement at 4 mm/s can be also achieved by 5 mm displacement at 64 mm/s speed. Therefore, our results virtually extend the limited travel distance of the tactor.

4 Conclusion and Future Work

We have designed a hand-held haptic device that applies tangential skin stretch to the palm via a tactor. We paid particular attention to making our device compact and ergonomic and achieve large tactor displacements and speeds. We then investigated the effects of tactor speed, displacement, direction and device orientation on the perceived magnitude of skin stretch. Due to the anatomy of the human palm, we were able to consider larger tactor displacements and speeds in our study compared with the previous studies of skin stretch applied to fingertip [6, 16]. The earlier studies in the palm have mainly focused on the effect of tactor displacement and showed that the perceived magnitude of skin stretch increases with the displacement. On the other hand, our results show that not only the tactor displacement but also its speed has a significant effect on the perceived magnitude of skin stretch. Furthermore, due to the asymmetrical distribution of mechanoreceptors in the palm, we observed a significant difference between the perceived stretch magnitudes of the radial (up) and ulnar (down) aspects (directions). In the future, we plan to conduct more experiments to investigate the individual effects of stimulus location and direction on the perceived stretch magnitude for multiple locations on the human palm. Our result, could be used in skin stretch interfaces, especially for gaming, to virtually extend the physical travel distance of tactor/s on the skin stretch device to produce haptic richer effects.

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