In Contact: Pinching, Squeezing and Twisting for Mediated Social Touch

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Abstract
Mediated social touch has the potential to enhance our interactions with machines and with each other. We present three wearable tactile devices that generate affective haptic sensations via three localised skin stretching modalities; pinching, squeezing, and twisting. The Pinch device is adhered to the skin of the forearm, generating pinching sensations in three locations. The Squeeze and Twist devices are wristbands that elicit squeezing and twisting sensations on the skin of the wrist. All of these devices are powered by shape memory alloy actuators, enabling them to be quiet, lightweight and discreet wearable interfaces, unlike their vibrotactile or servo-motor driven counterparts.

We investigate the potential for these devices to be used in mediated social touch interactions by conducting preliminary psychometric tests measuring affective response. The Pinch device and Squeeze wristband were found to simulate positive affective touch sensations, particularly in comparison to vibrotactile stimuli.

Author Keywords
Tactile Devices and Interfaces; Wearables; Mediated Social Touch.

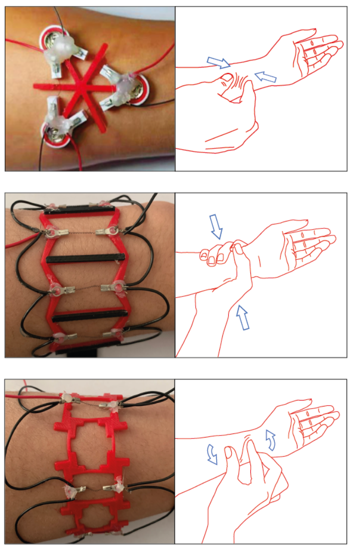

Figure 1: The three wearable haptic devices designed in this study; Pinch, Squeeze and Twist (top to bottom) and illustrations of the human touch interactions they simulate.

CCS Concepts

•Human-centered computing → **Human computer interaction (HCI);** *Haptic devices;* User studies;

Introduction

Research on human touch has largely focused on discriminative touch for sensing, but recent studies have recognised the importance of affective touch and its role in social interactions [17, 7]. These findings support the growing field of research into haptic devices for mediated social touch [13], allowing people to communicate remotely via touch.

Existing devices generally use vibration or motor-driven force to generate sensations on the skin that either replicate actual social touch (e.g. a handshake [19] or hug [25]) or communicate higher-level symbolic meaning between communicating parties [12]. Recently, however, there has been research into other methods of stimulation in an attempt to generate more natural and localised sensations [13]. To create mediated social touch interactions that are accessible on-the-go throughout a person's daily routine, such devices need to be wearable, comfortable and discreet.

We present three wearable devices and investigate their ability to convey emotive touch sensations. The devices are designed to simulate three forms of human touch; pinch, squeeze and twist, as illustrated in figure 1. The Pinch device (figure 1 top) is based on our previous skin-stretching device [9]. Its triangular configuration provides more degrees of freedom with subsequent different alignments of skin stretching on the forearm. The Squeeze and Twist devices are designed as wristbands, one which contracts to squeeze the wrist (figure 1 middle) and one which has rotating elements to twist the skin (figure 1 bottom). We investigate the emotive responses of wearers to these different sensations.

Related Work

The majority of existing haptic interfaces are vibration based. Efforts have been made to anthropomorphise vibrotactile feedback such as the CheekTouch [21] and ForcePhone [11] which use vibration patterns to signify different social interactions. The TaSST is a vibrotactile sleeve used for mediated social touches [14] such as for conveying squeezing and stroking. Tsetserukou *et al.* [27] created a number of devices to elicit various human feelings. They used vibration to simulate tickling, shivering and butterflies in the stomach and a speaker on the chest conveyed the other person's heartbeat.

While vibration motors are low cost, compact and effective, they are limited in the range of sensations they can elicit. Vibrotactile stimuli activate the fast-acting mechanoreceptors (the Meissner and Pacinian corpuscles) within the dermis which have a relatively large perceptive field. Skin stretching sensations, on the other hand, can also activate the slow-acting mechanoreceptors (Ruffini endings and Merkel's disks) [5, 1] that have smaller receptive fields and process localised force information. Skin stretching is also capable of activating the CT afferents in human hairy skin which process social and affective touch [20]. This evidence suggests that vibrotactile stimuli alone may not be sufficient to simulate diverse and meaningful affective touch sensations.

Existing skin-stretch devices and interfaces can be categorised by their location on the body. Finger-tip displays are commonly used [23, 6, 18, 26, 10, 4] for providing natural discriminative touch feedback in virtual situations. These devices are generally powered by servo-motors that move linkages or belts to create shear forces on the pad of the finger [23, 6, 18], or independently move metal pins on the skin surface [10, 4]. Some of these devices are wear-

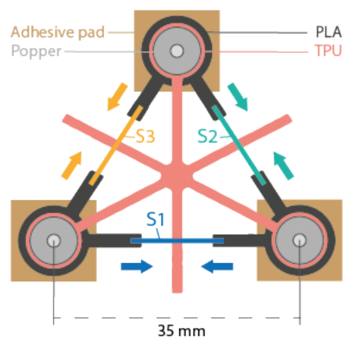

Figure 2: Pinch device structure. Arrows indicate the respective contraction of SMA coils S1, S2 and S3.

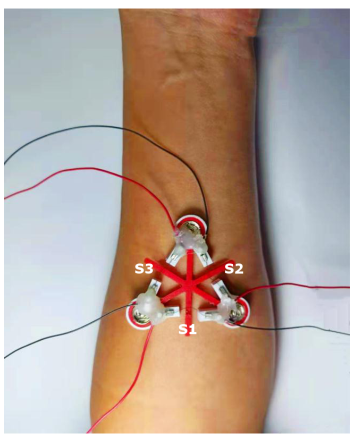

Figure 3: Orientation of the Pinch device on a user's forearm.

able [18, 26], but fingertip displays are generally only practical for specific interaction tasks rather than for wearing throughout the day.

Skin-stretching or squeezing devices have also been designed for the back of the hand [29], wrist [15, 24, 16], forearm [1, 2] and upper arm [3, 28]. These devices have been shown to provide intuitive proprioception information [1, 3], navigation information [2, 16], motion guidance [29] and affective touch [15, 28, 24, 8]. Most of these devices generate sensations by a motor-driven end effector that moves tangential to the skin [1, 16, 2, 3, 29, 24]. Most of these are wearable interfaces, but the motors and casings mean that they are bulky and potentially noisy. Some devices have overcome these factors by using shape memory alloys (SMAs) to generate skin stretching [15, 8].

Of these devices, those that were designed for affective touch or mediated social touch have aimed to simulate real human interactions. Stanley and Kuchenbecker [24] created wrist-worn devices to simulate four types of human touch; tapping, dragging, squeezing, and twisting. The sensations were generally found to be comparable to human touch and participants reported that squeezing in particular felt natural and pleasant. Wang *et al.* created a servo-motor driven device that squeezes a listeners arm at specific times during a story. They found that it increased the listener's sense of connectedness with the storyteller [28]. Knoop and Rossiter [15] created a wearable wristband designed to gently stroke the user's skin as a method of conveying affection and emotion. Hamdan *et al.* [8] used SMAs attached to pads adhered to the skin in a number of ways to generate six different tactile sensations: pinching, directional stretching, pressing, pulling, dragging, and expanding.

Skin-Pinching Device

Device Design

The Pinch device (figures 2 and 3) consists of two structural 3D printed parts (Wanhao Duplicator i3). The red part is printed with a flexible filament (TPU) and has six equal legs. At the end of three of those legs are circular rings within which poppers were attached and under which adhesive pads attached the device to the skin. Rigid reinforcement elements were 3D printed from PLA to strengthen the rings (shown in black in figure 2). The three shape memory alloy (SMA) coiled wires (BioMetal Helix, BMX series 15000) were attached to the ends of these rigid elements to create a triangular shaped device.

User Study

10 volunteers (7 males, 3 females) were asked to wear the device on the inside of their forearm orientated as shown in figure 3. Each SMA on the device was separately activated at three voltages (1.67 V, 2.5 V and 5 V), as described in [9], and participants were asked to rate the strength and pleasantness of the sensation on a scale of 1-10, consistent with the Circumplex model of affect [22]. For comparison with existing devices, participants were asked to wear the Pinch device, the previous version [9] and a smart watch which provided vibration stimuli. Participants were asked which sensation(s) they preferred out of these devices.

To determine whether the device could be used to convey information, the three different SMAs were actuated and participants were asked to choose which SMA they thought had been activated. To investigate how subtle the device is, participants were asked to record each time they noticed a sensation from the device while they were doing nothing, reading a book or playing a game. The percentage of correctly noticed activations was recorded.

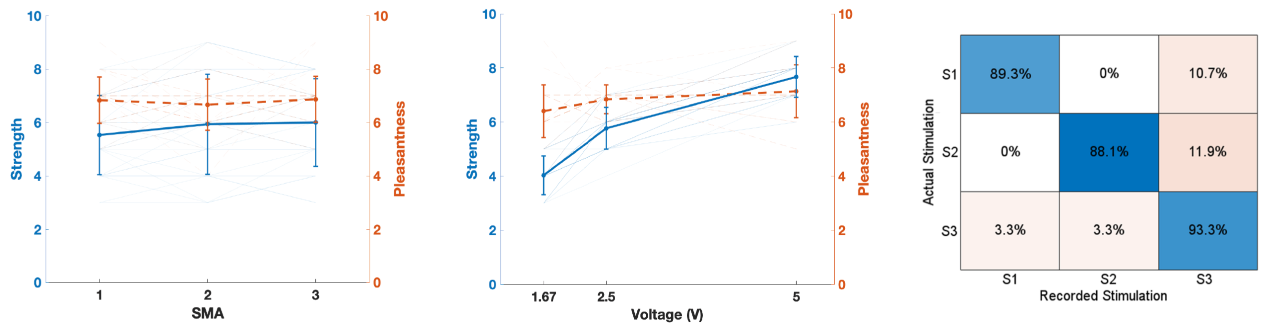

Figure 4: Left and middle: Perceived strength (blue solid) and pleasantness (orange dashed) across all participants for each SMA S1, S2 and S3 at all voltages (left) and against activation voltage (middle). Bold lines represent mean responses, error bars represent 1 standard deviation. Right: Confusion matrix of the activated SMA S1, S2 or S3 and the perceived location of stimulation.

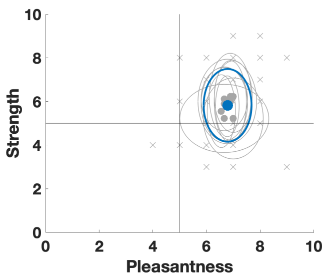

Figure 5: Perceived strength vs pleasantness of the Pinch device across all participants and voltage levels. Mean and standard deviation of all responses shown in blue (bold); individual participant responses, means and standard deviations in grey.

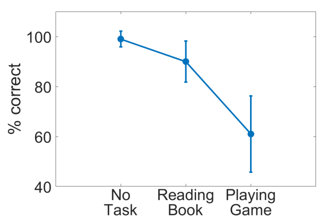

Figure 6: Accuracy of detecting Pinch device stimulation whilst undertaking three different tasks.

Results

As shown in figure 5, participants consistently found the Pinch device pleasant with little variation between participants. All participants reported that they preferred the sensations generated by the Pinch device and the previous skin-stretching device in comparison to vibration.

There was no significant difference (Welch's t-test at 10% significance) between the SMA positions for both perceived strength and pleasantness (figure 4 left), but there is a positive Pearson correlation coefficient (r-val=0.866; p-val=0.000) between perceived strength and the voltage of activation (figure 4 middle). Pleasantness is slightly increased by increased voltage (r-val=0.314; p-val=0.003).

Participants were able to correctly determine which SMA was activated with 90% mean accuracy. From the confusion matrix (figure 4 right) it can be seen that all incorrect responses for SMA wires S1 and S2 stimulation were recorded as S3 stimulation (i.e. S3 had the most false positive responses). S3 also generated the fewest incorrect responses. This could be an indication that the location or direction on the forearm that SMA wire S3 stimulates is more sensitive than the areas stimulated by S1 and S2.

When participants were distracted by tasks that took more concentration they were significantly less accurate at noticing pinch sensations (supported by Welch's t-test at 1% significance showing statistical independence); their % correctly noticed sensations was 99% for no task (std 3.2%), 90% when reading (std 8.2%) and 61% when playing a game (std 15%), as shown in figure 6. In the previous study [9] it was found that vibration stimuli were consistently noticed (mean 99%) during all tasks. This suggests that the Pinch device is able to convey subtle alerts where the user is less likely to be disturbed when involved in a task that requires more concentration, but when they are not focusing on a task they notice the sensations.

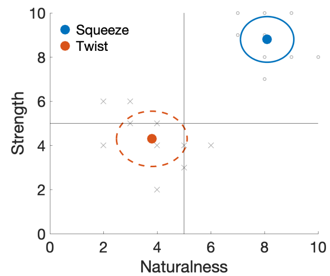

Figure 7: Perceived strength and naturalness for the Squeeze and Twist wristbands across all participants. Mean and standard deviation shown in bold for Squeeze (blue solid, o markers) and Twist (orange dashed, x markers).

Figure 8: Histogram of the users' responses (where frequency indicates number of responses) on the effectiveness of the Squeeze (orange stripes) and Twist (blue solid) wristbands as an interaction device when activated by another person.

Participant's comments were generally positive with people stating that the Pinch device felt "like a real human hand" and "like someone is touching me". They also commented on the the fact that the Pinch device "is really quiet and doesn't affect me and distract my attention" and "it's lightweight and doesn't put an extra burden on my arm". There were, however, some users who felt that the device had too many wires for it to be practical and that "the tactile feeling it brings does not appeal to me".

Squeeze and Twist Wristbands

Device Design

Both wristbands are based on auxetic structures. The Squeeze wristband (figure 9 top) is made up of seven re-entrant hexagons placed end-to-end. It is 3D printed (Wanhao duplicator i3) from flexible filament (TPU). The coiled SMAs are attached along the centre of each auxetic unit. To avoid buckling of the wristband, PLA printed rods were glued to the structure between each unit (shown in black in figure 9 top). Actuation of the SMAs causes the structure to shorten and to squeeze the wrist. The Twist wristband (figure 9 bottom) is made up of a connection of crosses. Four crosses combine to make one auxetic unit. The wristband consists of nine auxetic units arranged alternating to 90°. Actuation of the SMAs causes each cross to rotate and to twist the skin. Both wristbands have adjustable velcro straps to ensure a secure fastening on the wrist and direct skin contact.

User Study

10 volunteers (8 males, 2 females) participated in this part of the study. The wristbands were worn on the user's wrist and participants were asked to rate on a scale of 1-10 the strength of the device and how natural the generated sensations felt. The participants were then asked to compare these sensations to that of a vibration device such as those found in a mobile phone for alerts. To test the devices as a

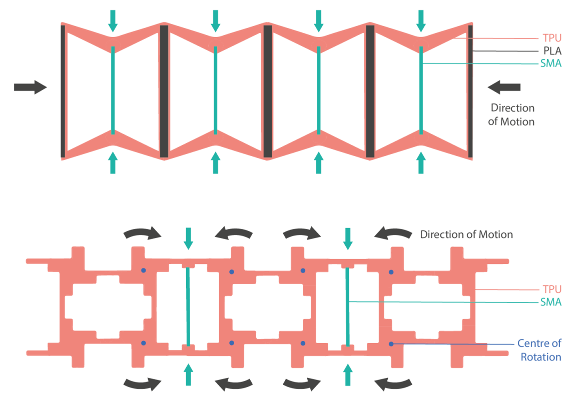

Figure 9: Structural diagrams of the Squeeze (top) and Twist (bottom) wristbands, illustrating subsections of the whole devices.

means of long-distance interactions, a second participant activated the device remotely and the wearer was asked to rate out of 10 how effective they felt the interaction was in the context of using the device for mediated social interactions. At the end of the experiment participants were asked for feedback on the device.

Results

The results show that the Squeeze wristband felt stronger and more natural than the Twist wristband (figure 7). When asked to compare the wristbands to vibration, participants found the Squeeze and Twist devices more natural with a mean rating of 9.3 (std 0.8) and 6.8 (std 1.0) respectively. Participants found the Squeeze wristband more effective than the Twist wristband when used as a remote device and activated by another person, with a mean effectiveness rating of 7.2 (std 1.0) for the Squeeze wristband and 4.2 (std 1.0) for the Twist wristband (figure 8).

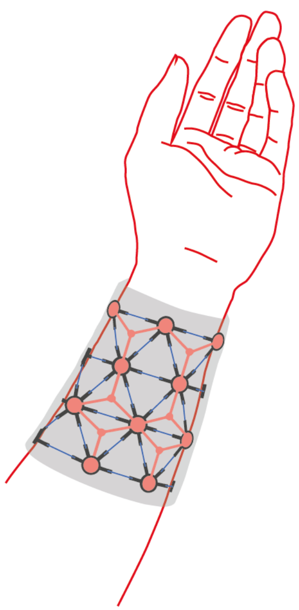

Figure 10: Illustration of what a future device design could look like; a wearable sleeve containing elements of the Pinch device in an array that is capable of eliciting a range of simulated human touches.

Participant's comments indicated that the wires were impractical and suggested making the wristbands remote controlled. Future iterations of the devices can address this. Some participants commented that the rotation wristband did not generate strong enough sensations for them to really feel or appreciate the twisting motion. We will undertake further design iterations to generate more effective twisting sensations. Aside from these suggested improvements, participants commented that they liked the wristband devices as they were not bulky or noisy.

Discussion

Pleasant sensations were generated by the Pinch device (figure 5) which was preferred to vibrotactile sensations. The location of actuation (S1, S2 or S3) did not correlate to pleasantness. However, figure 4 (right) suggests that the area of the forearm at S3 is most sensitive as participants had the least incorrect responses to this stimulation and all incorrect responses for S1 and S2 were recorded as S3.

The Pinch device was able to provide information of different strengths as participants recorded an increase in perceived strength as voltage increased from 1.67V to 5V (figure 4 middle). This gives the Pinch device the potential to use different levels of voltages on the skin to simulate different sensations or to symbolise emotive meaning.

As concentration on a task increased, participants were less accurate at detecting sensations generated by the Pinch device; comparing no task, reading and playing a game (figure 6). The Pinch device could therefore be used as a means of providing subtle alerts that do not disturb the user when concentrating on work or driving, for example.

The Squeeze wristband was also able to provide natural sensations (figure 7). An advantage of it over the Pinch and previous skin-stretching device is that it is worn as a wristband rather than adhered to the skin and is therefore more practical as a wearable device. The Squeeze wristband was more effective at generating natural sensations compared to the Twist wristband (figure 7). When used as a communication device between two people, the Squeeze wristband was more effective at providing stimulations compared to the Twist wristband (figure 8).

Conclusion and Future Work

We have demonstrated that affective touch can be achieved with skin-manipulating devices that are preferred over devices using vibrotactile sensations. We have shown that SMA-driven devices are capable of generating Pinch and Squeeze sensations on the skin that are pleasant and natural. The Twist sensation was less effective, however this could potentially be enhanced by adding points of contact to improve skin coupling.

Further development of these devices will predominantly focus on making them untethered and remote controlled so that they can be truly wearable. This will allow us to test their effectiveness in real social interactions, outside of a laboratory environment.

Another area of interest for future work is to combine multiple Pinch units together to form a modular network of skin-stretchers as illustrated in figure 10. This network can be embedded in fabric and worn discreetly underneath clothing. The modular format could become the haptic equivalent of a prototyping toolkit [30], allowing people to design personalised touch interactions. Having a network of skin-stretchers would greatly increase the capacity for providing information, at different locations, strengths and patterns.

With these further developments, the devices could be discreetly worn in daily life, giving people a means of both sending and receiving affective touch.

REFERENCES

[1] Karlin Bark, Jason W Wheeler, Sunthar Premakumar, and Mark R Cutkosky. 2008. Comparison of skin stretch and vibrotactile stimulation for feedback of proprioceptive information. In *2008 Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. IEEE, IEEE, Reno, NE, USA, 71–78.

[2] Francesco Chinello, Claudio Pacchierotti, Nikos G Tsagarakis, and Domenico Prattichizzo. 2016. Design of a wearable skin stretch cutaneous device for the upper limb. In *2016 IEEE Haptics Symposium (HAPTICS)*. IEEE, IEEE, Philadelphia, PA, USA, 14–20.

[3] Janelle Clark, Sung Kim, and Marcia O'Malley. 2018. *The Rice Haptic Rocker: Comparing Longitudinal and Lateral Upper-Limb Skin Stretch Perception*. Springer, Houston, USA, 125–134. DOI: http://dx.doi.org/10.1007/978-3-319-93399-3_12

[4] Michael Fritschi. 2003. Design of a Tactile Shear Force Prototype Display. In *TOUCH-HapSys*. 1–11.

[5] Esther P Gardner, John H Martin, and others. 2000. Coding of sensory information. *Principles of neural science* 4 (2000), 411–429.

[6] Brian T Gleeson, Scott K Horschel, and William R Provancher. 2010. Design of a fingertip-mounted tactile display with tangential skin displacement feedback. *IEEE Transactions on Haptics* 3, 4 (2010), 297–301.

[7] Antal Haans and Wijnand Ijsselsteijn. 2006. Mediated social touch: A review of current research and future directions. *Virtual Reality* 9 (01 2006), 149–159. DOI: http://dx.doi.org/10.1007/s10055-005-0014-2

[8] Nur Al-huda Hamdan, Adrian Wagner, Simon Voelker, Jürgen Steimle, and Jan Borchers. 2019. Springlets: Expressive, Flexible and Silent On-Skin Tactile Interfaces. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. ACM, New York, NY, USA, Article 488, 14 pages. DOI: http://dx.doi.org/10.1145/3290605.3300718

[9] A. Haynes, M. F. Simons, T. Helps, Y. Nakamura, and J. Rossiter. 2019. A Wearable Skin-Stretching Tactile Interface for Human-Robot and Human-Human Communication. *IEEE Robotics and Automation Letters* 4, 2 (April 2019), 1641–1646. DOI: http://dx.doi.org/10.1109/LRA.2019.2896933

[10] Vincent Hayward and Juan Cruz-hern. 2000. Tactile Display Device Using Distributed Lateral Skin Stretch. In *Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. ASME, Orlando, FL, USA.

[11] Eve Hoggan, Craig Stewart, Laura Haverinen, Giulio Jacucci, and Vuokko Lantz. 2012. Pressages: Augmenting Phone Calls with Non-verbal Messages. In *Proceedings of the 25th Annual ACM Symposium on User Interface Software and Technology (UIST '12)*. ACM, New York, NY, USA, Article 58, 8 pages. DOI: http://dx.doi.org/10.1145/2380116.2380185

[12] Gijs Huisman. 2012. A Touch of Affect: Mediated Social Touch and Affect. In *Proceedings of the 14th ACM International Conference on Multimodal Interaction (ICMI '12)*. ACM, New York, NY, USA, 317–320. DOI: http://dx.doi.org/10.1145/2388676.2388746

[13] Gijs Huisman. 2017. Social touch technology: A survey of haptic technology for social touch. *IEEE transactions on haptics* 10, 3 (2017), 391–408.

[14] G. Huisman, A. Darriba Frederiks, B. Van Dijk, D. Hevlen, and B. Kröse. 2013. The TaSSt: Tactile sleeve for social touch. In *2013 World Haptics Conference (WHC)*. IEEE, Daejeon, South Korea, 211–216. DOI: http://dx.doi.org/10.1109/WHC.2013.6548410

[15] Espen Knoop and Jonathan Rossiter. 2015. The Tickler: A Compliant Wearable Tactile Display for Stroking and Tickling. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '15)*. ACM, New York, NY, USA, 1133–1138. DOI: http://dx.doi.org/10.1145/2702613.2732749

[16] Yuki Kuniyasu, Michi Sato, Shogo Fukushima, and Hiroyuki Kajimoto. 2012. Transmission of forearm motion by tangential deformation of the skin. In *Proceedings of the 3rd Augmented Human International Conference*. ACM, ACM, Megève, France, 16.

[17] Francis McGlone, Johan Wessberg, and Håkan Olausson. 2014. Discriminative and affective touch: sensing and feeling. *Neuron* 82, 4 (2014), 737–755.

[18] Kouta Minamizawa, Souichiro Fukamachi, Hiroyuki Kajimoto, Naoki Kawakami, and Susumu Tachi. 2007. Gravity Grabber: Wearable Haptic Display to Present Virtual Mass Sensation. In *ACM SIGGRAPH 2007 Emerging Technologies (SIGGRAPH '07)*. ACM, New York, NY, USA, Article 8, 5 pages. DOI: http://dx.doi.org/10.1145/1278280.1278289

[19] Hideyuki Nakanishi, Kazuaki Tanaka, and Yuya Wada. 2014. Remote Handshaking: Touch Enhances Video-mediated Social Telepresence. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '14)*. ACM, New York, NY, USA, 2143–2152. DOI: http://dx.doi.org/10.1145/2556288.2557169

[20] Håkan Olausson, Johan Wessberg, India Morrison, and Francis Mcglone. 2016. *Affective Touch and the Neurophysiology of CT Afferents*. Springer-Verlag New York, New York, USA. DOI: http://dx.doi.org/10.1007/978-1-4939-6418-5

[21] Young-Woo Park, Chang-Young Lim, and Tek-Jin Nam. 2010. CheekTouch: An Affective Interaction Technique While Speaking on the Mobile Phone. In *CHI '10 Extended Abstracts on Human Factors in Computing Systems (CHI EA '10)*. ACM, New York, NY, USA, 3241–3246. DOI: http://dx.doi.org/10.1145/1753846.1753965

[22] Jonathan Posner, James A Russell, and Bradley S Peterson. 2005. The circumplex model of affect: An integrative approach to affective neuroscience, cognitive development, and psychopathology. *Development and psychopathology* 17, 3 (2005), 715–734.

[23] William R. Provancher, Katherine J. Kuchenbecker, Günter Niemeyer, and Mark R. Cutkosky. 2005. Perception of Curvature and Object Motion Via Contact Location Feedback. In *Proceedings of the International Symposium on Robotics Research (ISRR) (Springer Tracts in Advanced Robotics)*, Vol. 15. Springer, Siena, Italy, 456–465. Oral presentation given by Provancher in October of 2003.

[24] Andrew A Stanley and Katherine J Kuchenbecker. 2011. Design of body-grounded tactile actuators for playback of human physical contact. In *2011 IEEE World Haptics Conference*. IEEE, IEEE, Istanbul, Turkey, 563–568.

[25] Dzmitry Tsetserukou. 2010. HaptiHug: A Novel Haptic Display for Communication of Hug over a Distance. In *Proceedings of the 2010 International Conference on Haptics: Generating and Perceiving Tangible Sensations, Part I (EuroHaptics'10)*. Springer-Verlag, Berlin, Heidelberg, Article 49, 8 pages. http://dl.acm.org/citation.cfm?id=1884164.1884216

[26] Dzmitry Tsetserukou, Shotaro Hosokawa, and Kazuhiko Terashima. 2014. LinkTouch: A wearable haptic device with five-bar linkage mechanism for presentation of two-DOF force feedback at the fingerpad. In *2014 IEEE Haptics Symposium (HAPTICS)*. IEEE, IEEE, Houston, TX, USA, 307–312.

[27] Dzmitry Tsetserukou, Alena Neviarouskaya, Helmut Prendinger, Naoki Kawakami, and Susumu Tachi. 2009. Affective haptics in emotional communication. In *2009 3rd International Conference on Affective Computing and Intelligent Interaction and Workshops*. IEEE, Amsterdam, Netherlands, 1 – 6. DOI: http://dx.doi.org/10.1109/ACII.2009.5349516

[28] Rongrong Wang, Francis Quek, Deborah Tatar, Keng Soon Teh, and Adrian Cheok. 2012. Keep in Touch: Channel, Expectation and Experience. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '12)*. ACM, New York, NY, USA, Article 16, 10 pages. DOI: http://dx.doi.org/10.1145/2207676.2207697

[29] Vibol Yem, Mai Otsuki, and Hideaki Kuzuoka. 2015. *Development of Wearable Outer-Covering Haptic Display Using Ball Effector for Hand Motion Guidance*. Springer Japan, Tokyo, 85–89. DOI: http://dx.doi.org/10.1007/978-4-431-55690-9_16

[30] Kening Zhu and Shengdong Zhao. 2013. AutoGami: a low-cost rapid prototyping toolkit for automated movable paper craft. In *Proceedings of the SIGCHI conference on human factors in computing systems*. 661–670.