This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TOH.2019.2917072, IEEE Transactions on Haptics

Resonant Frequency Skin Stretch for Wearable Haptics

Peter B. Shull, *Member, IEEE,* Tian Tan, *Student Member, IEEE*,
Heather Culbertson, *Member, IEEE,* Xiangyang Zhu, *Member, IEEE*,
Allison M. Okamura, *Fellow, IEEE*

Abstract—Resonant frequency skin stretch uses cyclic lateral skin stretches matching the skin's resonant frequency to create highly noticeable stimuli, signifying a new approach for wearable haptic stimulation. Four experiments were performed to explore biomechanical and perceptual aspects of resonant frequency skin stretch. In the first experiment, effective skin resonant frequencies were quantified at the forearm, shank, and foot. In the second experiment, perceived haptic stimuli were characterized for skin stretch actuations across a spectrum of frequencies. In the third experiment, perceived haptic stimuli were characterized for different actuator masses. In the fourth experiment, haptic classification ability was determined as subjects differentiated haptic stimulation cues while sitting, walking, and jogging. Results showed that subjects perceived stimulations at, above, and below the skin's resonant frequency differently: stimulations lower than the skin resonant frequency felt like distinct impacts, stimulations at the skin resonant frequency felt like cyclic skin stretches, and stimulations higher than the skin resonant frequency felt like standard vibrations. Subjects successfully classified stimulations while sitting, walking, and jogging, perceived haptic stimuli was affected by actuator mass, and classification accuracy decreased with increasing speed, especially for stimulations at the shank. This work could facilitate more widespread use of wearable skin stretch. Potential applications include gaming, medical simulation, and surgical augmentation, and for training to reduce injury risk or improve sports performance.

Index Terms— Tactile Display, Vibration Feedback, Wearable Devices, Haptic Classification

1 INTRODUCTION

SKIN stretch is a rich haptic modality that can facilitate and deepen human-machine interactions. Skin stretch feedback, also known as skin deformation feedback, has shown a potential for enhancing virtual reality [1], [2], compensating for sensory impairments [3], augmenting myoelectric systems [4], and improving rehabilitation [5]. Skin stretch aids the perception of haptic stimuli as mechanoreceptors activate due to texture, friction, slip, and force sensations [6] including while grasping and manipulating objects [7]. Skin stretch has been used in conjunction with force feedback to bias stiffness and friction perception [8], [9]. Because vibration causes desensitization over time [10], can be uncomfortable [11], and is hard to distinguish when stimulations are close together in space or time [6], [12], skin stretch could potentially be used in place of or in conjunction with vibration for human machine haptic interactions.

- *P.B. Shull is with the State Key Laboratory of Mechanical System and Vibration, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China. E-mail: pshull@ sjtu.edu.cn.*
- *T. Tan is with the State Key Laboratory of Mechanical System and Vibration, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China. E-mail: alantantian@sjtu.edu.cn.*
- *H. Culbertson is with the Departments of Computer Science, and Aerospace and Mechanical Engineering, University of Southern California, Los Angeles, CA 90089, hculbert@usc.edu*
- *X. Zhu is with the State Key Laboratory of Mechanical System and Vibration, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China. E-mail: mexyzhu@ sjtu.edu.cn.*
- *A.M. Okamura (corresponding author) is with the Department of Mechanical Engineering, Stanford University, Stanford, CA 94305. E-mail: aokamura@stanford.edu.*

Mechanoreceptors, embedded throughout human skin, are responsible for sensing skin stretch and other haptic stimuli and relaying this information to the brain [13]. In general, slow adapting mechanoreceptors sustain their response level throughout the stimulus and are responsible for the perception of spatial properties, while rapidly adapting mechanoreceptors exhibit a short, transient response at the beginning of stimulation and are responsible for the perception of temporal properties [14]. Specifically, Meissner corpuscles respond to lower frequency skin stretch and vibration, and Ruffini endings sense higher frequency skin stretch and stretch direction [15]. Pacinian corpuscles respond to higher frequency vibrations and transient contacts, and Merkel disks detect pressure and fine details such as edges and spatial features [16]. The above characterizations are generally true, but certain skin stimulation frequencies (e.g. between 3-100 Hz) activate multiple types of mechanoreceptors simultaneously [15], [17], [18] potentially creating rich and complex perceived sensations.

Haptic perception is in fact largely influenced by the frequency of skin stimulation. Skin stretch stimulation frequency has a profound effect on the discharge rates of all types of mechanoreceptors [19], and the speed of skin stretch thus significantly affects perceived intensity and magnitude [20]. Stimulation frequencies below approximately 3 Hz may be perceived as slow kinesthetic motion, from 10-70 Hz as rough motion or fluttering, and above 100 Hz as smooth vibration [21]. Human perception is also largely influenced by stimulation frequency in other haptic

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TOH.2019.2917072, IEEE Transactions on Haptics

stimulation modalities such as for vibration stimulation [22] or finger stroke along the skin [23]. The speed of motion of touch stimulation along the skin significantly affects the perceived distance travelled [24], and the frequency of skin taps can profoundly affect perception [25]. Perceived tactile and haptic illusions often rely on the frequency of stimulation [26]. While current skin stretch applications primarily target lower frequencies (i.e. less than 10 Hz) [3], [13], [27], higher frequency skin stretch stimulation could evoke additional varied haptic perceptions. In addition, activating skin stretch at the skin's resonant frequency can provide these higher activation frequencies while at the same time leveraging the inherent properties of resonant frequency motion to increase stretch displacement during stimulation.

In this paper, we introduce resonant frequency skin stretch as a new approach for haptic stimulation. To accomplish this, skin is cyclically stretched at the frequency matching the skin's resonant frequency for a given location. We first provide relevant background research related to previous skin stretch approaches and then describe a custom prototype to implement the resonant frequency skin stretch for wearable applications. We then present three experiments to explore various aspects of resonant frequency skin stretch. In the first experiment, skin resonant frequencies are quantified at the forearm, shank, and foot. In the second experiment, perceived haptic stimuli is characterized for skin stretch actuations across a spectrum of frequencies including at, above, and below skin resonance. In the third experiment, we determined the ability of subjects to differentiate haptic stimulation cues at the skin resonant frequency from other haptic cues while sitting, walking, and jogging. We conclude by discussing the results of these experiments and future implications.

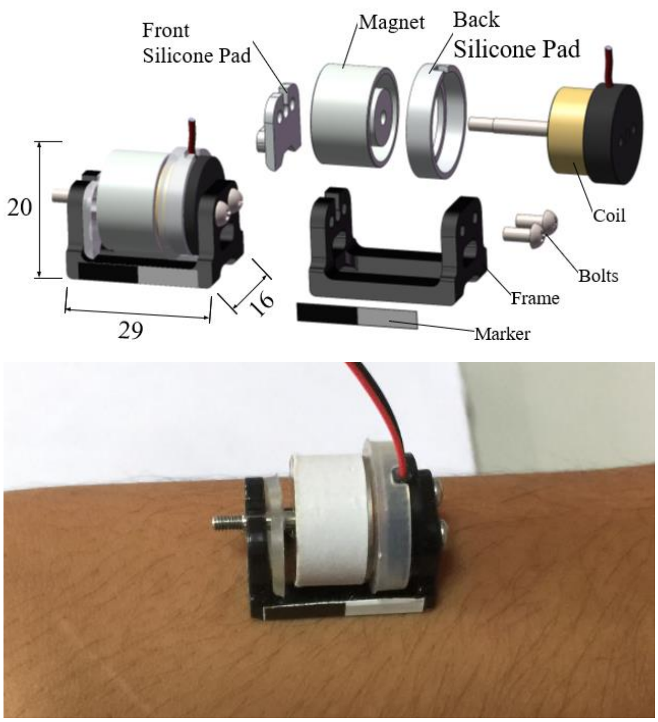


Figure 1. Wearable skin stretch (top) 3D schematic and (bottom) physical prototype attached to the skin via hypoallergenic, double-sided tape. The overall size is 29 × 16 × 20 mm, and the weight is 18.4g.

2 Related Skin Stretch Research

Fingertips are often targeted for skin stretch applications, likely because of the high density of mechanoreceptors [28]. Gleeson et al. [29] showed that subjects could distinguish four skin stretch directions at the fingertip with as little as 0.2 mm of tangential displacement and at speeds as slow as 1 mm/s. Further research resulted in handheld devices that produce lateral thumb and index fingertip skin stretch for potential gaming applications [30], [31]. Girard et al. [32] developed a wearable fingertip system to simulate 2-degree-of-freedom shear forces at the fingertip to display virtual surface textures and virtual object inertias and weights. Users were able to discriminate skin stretch directions and perceive differing virtual object weights. This idea was further extended to 3-degree-of-freedom wearable fingertip devices, e.g. [33], which could potentially function as a surrogate for traditional grounded kinesthetic haptic display by displaying mechanical properties of virtual environments.

Skin stretch has also been used to create haptic sensations at various other locations across the human body. Skin stretch on the fingers, hands, and wrist has been shown to improve driving, rehabilitation, and gaming [20], [34], [35]. Asymmetric vibrations have also been used to produce skin deformation along the fingers and elicit translational and rotational guidance cueing sensations [36], [37]. Yem and Kajimoto [38] developed a wearable tactile device that combines electrical and mechanical stimulation along the fingers to selectively stimulate skin sensory mechanoreceptors and provide tactile feedback of virtual objects. Rotational skin stretch applied to the forearm can be used to provide proprioceptive feedback for a virtual prosthetic arm [4], and wearable forearm skin stretch can provide direction cues for navigation [39]. Forearm skin stretch, when combined with a haptic joystick, can improve motor task performance for the elderly [40]. Finally, rotational skin stretch applied to the lower back can be a natural way to train mediolateral trunk sway during gait [41], and lateral skin stretch applied to the lower leg has the potential to function as a feedback modality for human movement training [42].

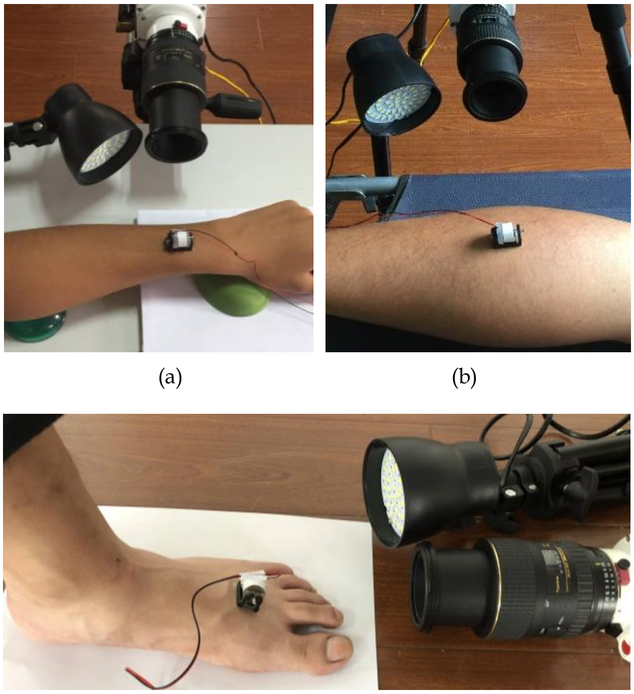
Skin stretch devices are generally either grounded to fixed objects or grounded to the human body. For skin stretch applications in laboratory settings [29], [43], devices can be grounded to tables, benches or other stationary objects. In contrast, for wearable implementations, skin stretch devices are typically grounded to the body by strapping the device around a limb or the torso [5], [40], [41], [44], [45]. In our wearable approach, a skin stretch device is taped to the skin to allow free movement and elicit natural frequency resonance in the skin during actuation. We thus focus on a wearable approach, toward enabling widespread adoption of haptics in portable applications.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TOH.2019.2917072, IEEE Transactions on Haptics

3 Wearable Skin Stretch Prototype

We designed a wearable, resonant frequency skin stretch prototype comprised of a frame, a voice coil motor (GVCM-016-010-01, Moticont, USA), two silicone pads, and two bolts (Fig. 1). This voice coil motor was chosen because of its internal bearings and compact size. The motor coil is wound around a cylindrical plastic case and fixed to the frame with the two bolts. The magnet of the voice coil motor fits in the coil and reciprocates along the shaft between the two silicone pads with a maximum axial displacement of 2 mm. Double-sided, hypoallergenic tape was used to attach the device to each skin location. A black and gray marker was adhered to the device body (Fig. 1) to visually track device movement during testing. The magnet acts as the moving proof mass and has a mass of 10 g.

During actuation, device movement is generated by the kinetic impulse from the magnet which strikes silicone pads for all actuation frequencies, and the movement frequency is controlled by the interval duration between impulses. Pilot studies indicated that without the silicone pads, device impulse collisions would be noisy and uncomfortable for subjects. The system is controlled via an Arduino Mega microcontroller board, which sends frequency and direction control signals to a voice coil motor driver (800-01, Moticont, USA). A 7.4V battery was used to power the motor, and a 62.5 kHz PWM cyclic square wave with changing signs at a specific frequency with a 43% duty cycle was used for all haptic experiments as described in the sections below. The PWM frequency was a standard value in the controller and the duty cycle was selected as a minimum duty cycle based on pilot testing such that subjects could easily perceive haptic sensations for stationary and movement testing. Testing with a high-speed video camera (Phantom M310, AMETEK, USA) determined that the maximum voice coil bandwidth was significantly higher than 50 Hz, which was the maximum actuation frequency for all testing in the haptic experiments described in the sections below.



(a) (b) (c)

Figure 2. Skin resonance experimental setup showing the device at the (a) left posterior forearm, (b) left posterior shank and (c) left top of foot. A high-speed camera was used to track device position during testing.

4 Experiment I: Skin Resonance Characterization

An initial experiment was conducted to determine human skin resonant frequency with the wearable haptic device attached at three distinct locations on the body: the forearm, the back of the shank, and the top of the foot. These three locations were chosen based on previous research suggesting that the skin receptors at these locations are typically underutilized during daily, outside-the-lab activities [5], [42], [46] and thus may be available for haptic stimulation in practical applications. In this and other following experiments, we also sought to systematically characterize and compare biomechanical and perceptual aspects of resonant frequency skin stretch across these three skin locations.

4.1 Experimental Testing

Ten healthy subjects (ages 21-24, all male) without any adverse dermatological conditions or known sensory deficits participated in this study, which was performed in accordance with the Declaration of Helsinki. Skin resonance was characterized on each subject's left forearm, shank and top of the foot (Fig. 2). For forearm skin resonance testing, subjects placed their forearm on two soft cushions with their palm facing down, and the device was located on the posterior surface of the left forearm above extensor digitorum tendons, roughly 30 mm from the wrist joint (Fig. 2a). For shank skin resonance testing, subjects laid face down on a foldout bed, and the device was located on the posterior surface of left shank above gastrocnemius, roughly 150 mm below the posterior cruciform ligament (Fig. 2b). For foot skin resonance testing, subjects sat in a chair with the foot resting flat on the ground, and the device was located on the top of the left foot above the second metatarsal, roughly 20 mm from the base of second toe (Fig. 2c). For all testing, the device was taped to the skin via hypoallergenic, double-sided tape.

Based on preliminary device testing to capture the full range of skin resonant frequencies, a 1-24 Hz square-wave chirp signal with frequency rising linearly at 2 Hz/s [47] was used to stimulate skin movement at each skin location. Subjects rested 15 minutes between each of the three trials during which time the device was moved to the next skin location. Device movement was captured by a high-speed camera (M310, Phantom, USA), at 2000 frames/second, and an external LED photographic light was used to ensure there was sufficient light (Fig. 2).

4.2 Data Analysis

To measure skin motion during skin deformation, the

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TOH.2019.2917072, IEEE Transactions on Haptics

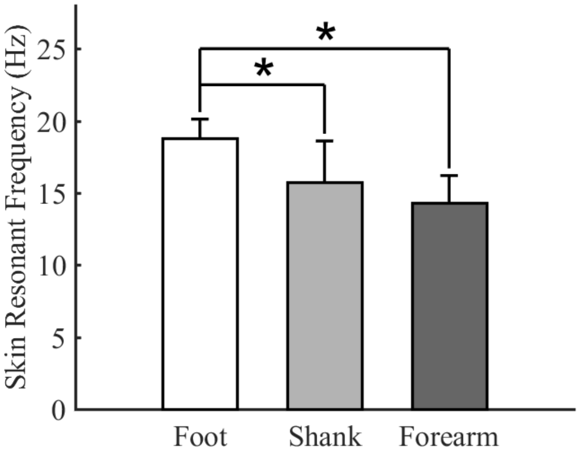


Figure 3. Mean measured skin resonant frequency at the forearm, foot, and shank for all subjects (n = 10). The foot had a higher skin resonant frequency than the forearm and shank. Error bars are one standard deviation, and (*) denotes statistically significant differences between locations (p < 0.05).

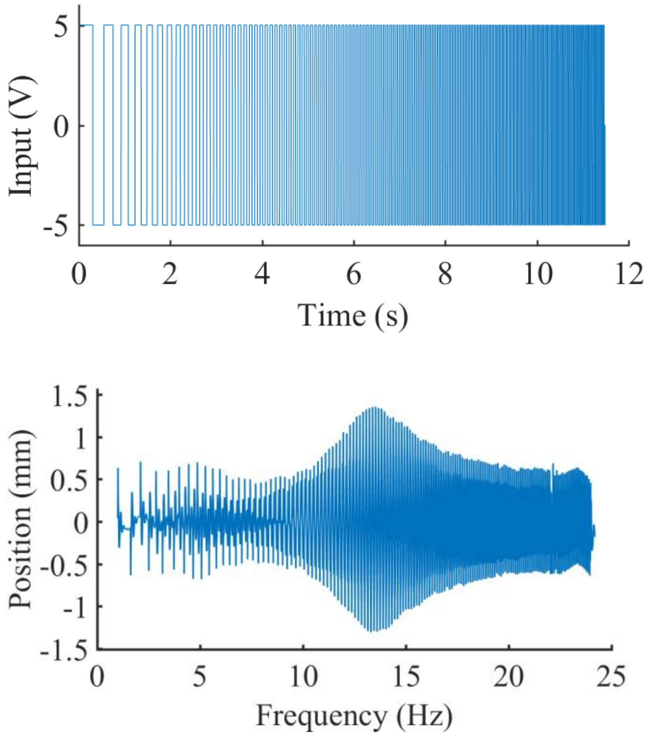


Figure 4. Representative trial for skin resonance characterization testing with square wave chirp input (top) resulting in resonant frequency output (bottom) during stationary testing. The testing location was the forearm, and the resulting resonant frequency was 13.5 Hz.

lateral position of the black and gray junction of the marker attached to the device body (Fig. 1) was tracked via edge detection image processing and was assumed to be the same as the lateral position of the skin directly attached to the device body. During image processing, noise was first removed via median filtering by replacing every pixel by the median value of its 10 row × 2 column neighborhood. The filtering matrix was shaped as a rectangle because the black and gray edge is a vertical line. The Canny algorithm was then used to determine the black and gray edge lateral position during each frame [48]. In this way, skin position was tracked throughout the span of the chirp signal during each trial, and the skin resonant frequency was determined as the frequency of maximum skin displacement with respect to the starting position. A one-way repeated-measures ANOVA was performed to determine whether resonant frequencies were different among skin locations; in the case of a difference, Tukey's post hoc analysis was used to determine differences between the pairs of skin locations. Data analysis was performed using MATLAB (MathWorks, Natick, MA, USA), and statistical significance was set to the level of $p = 0.05$.

4.3 Results

Results showed that skin resonant frequencies with the wearable haptic device were in the range of 10-20 Hz (Fig. 3). ANOVA results showed that the skin location had a significant effect on the resonant frequency ($F(2, 27) = 11.5$, $p < 0.05$), and post hoc testing showed that skin on the foot had a higher resonant frequency (mean 18.8 Hz) than skin on the shank (mean 15.8 Hz) or forearm (mean 14.3 Hz) ($p<0.05$). Figure 4 shows a representative trial depicting the characteristic increase in skin displacement amplitude at the skin resonant frequency.

5 Experiment II: Perceived Haptic Stimuli – Different Skin Locations

Based on results from the initial skin resonance characterization experiment, a second experiment was conducted to characterize perceived haptic stimuli of skin stretch actuation frequencies at, above, and below skin resonant frequencies. Qualitatively, in pilot testing, lower frequency stimuli felt like distinct impacts, resonant frequency stimuli felt like cyclic skin stretches, and higher frequency stimuli felt like standard vibrations. Thus, this experiment sought to quantify the frequency ranges of these perceived haptic stimuli.

5.1 Experimental Testing

Ten healthy subjects (ages 21-26, all male) without any adverse dermatological conditions or known sensory deficits participated in this study (eight were the same subjects as in the skin resonance characterization experiment), which was performed in accordance with the Declaration of Helsinki. Each subject performed a set of three sitting trials while wearing the haptic device (Fig. 1) at the forearm, shank, and foot for a total of nine trials. Subjects wore headphones and soundproof earplugs to avoid receiving audio cues, and eye coverings to avoid receiving visual cues. The haptic device was taped to the skin via hypoallogenic, double-sided tape.

During each trial, a series of haptic stimuli were presented to the subject at frequencies of 2, 4, 6, …, 50 Hz following the same waveform as in Experiment I. Haptic stimuli at each frequency were presented twice for a total of 50 stimuli for each trial. Each haptic stimulus lasted 0.5 sec and was presented in random order every 2 to 6 seconds. Subjects were not explicitly trained how to map example stimulations to specific sensations (distinct impact, cyclic, skin stretch, or standard vibration). Rather, subjects

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TOH.2019.2917072, IEEE Transactions on Haptics

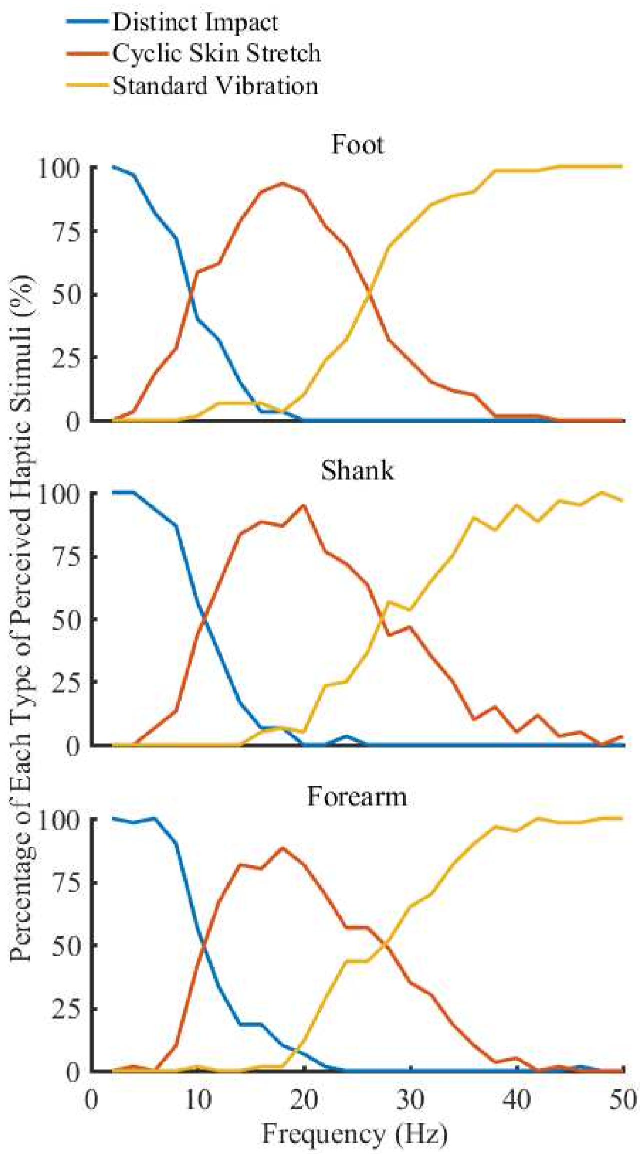


Figure 5. Perceived haptic stimuli testing results for stimuli characterized as distinct impact, cyclic skin stretch, and standard vibration across a spectrum of frequencies on the forearm, foot, and shank.

were instructed to verbally report after each stimulus during testing whether it felt like a distinct impact, cyclic skin stretch, or standard vibration, and answers were recorded by a research staff member.

5.2 Data Analysis

Perceived haptic stimuli were recorded and the proportion of each type of stimulus was computed for all subjects for forearm, foot, and shank. For each location, the percentage of haptic cues perceived as impact, resonant frequency or vibration were computed across all frequencies from 2-50 Hz.

5.3 Results

In general, haptic stimuli at frequencies below the resonant frequency were perceived as distinct impacts, frequencies at the resonant frequency were perceived as cyclic skin stretches, and frequencies above the resonant frequency were perceived as standard vibrations (Fig. 5). Across all skin locations, the majority of haptic stimuli were perceived as distinct impacts for actuation frequencies of 8 Hz or lower. Similarly, the majority of haptic stimuli were perceived as standard vibrations at frequencies of 28 Hz or higher.

Figure 6. Wearable skin stretch device with (left) no mass added, (middle) 20g mass added, and (right) 40g mass added.

6 Experiment III: Perceived Haptic Stimuli – Different Actuator Masses

A third experiment was performed to explore the influence of actuator mass on perceived haptic stimuli. In particular, we sought to determine how increasing actuator mass changes perceived cyclic skin stretch.

6.1 Experimental Testing

Ten healthy subjects (ages 21-26, all male) without any adverse dermatological conditions or known sensory deficits participated in this study (same subjects as in the skin resonance characterization experiment), which was performed in accordance with the Declaration of Helsinki. Each subject performed a set of three sitting trials while wearing the haptic device with different masses at the forearm.

Subjects performed testing wearing the wearable skin stretch device on the forearm (Fig. 1a) under 3 conditions: 1) no mass added, 2) 20g mass added, and 3) 40g mass added (Fig. 6). Subjects wore headphones and soundproof earplugs to avoid receiving audio cues, and eye coverings to avoid receiving visual cues. The haptic device was taped to the skin via hypoallergenic, double-sided tape.

During each trial (1 trial for each of the 3 conditions), a series of haptic stimuli were presented to the subject at frequencies of 2, 4, 6, …, 40 Hz. Haptic stimuli at each frequency were presented twice for a total of 40 stimuli for each trial. Each haptic stimulus lasted 0.5 sec and was presented in random order every 2 to 6 seconds. Subjects were not explicitly trained how to map example stimulations to specific sensations (distinct impact, cyclic skin stretch, or standard vibration). Rather, subjects were instructed to verbally report after each stimulus during testing whether it felt like a distinct impact, cyclic skin stretch, or standard vibration, and answers were recorded by a research staff member.

6.2 Data Analysis

Perceived haptic stimuli were recorded and the proportion of haptic stimuli perceived as cyclic skin stretches

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TOH.2019.2917072, IEEE Transactions on Haptics

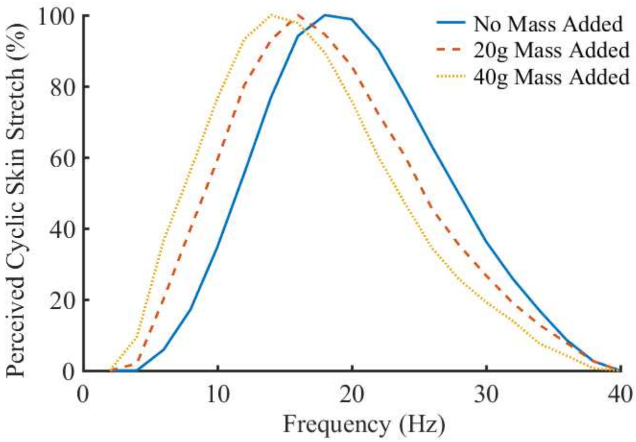


Figure 7. Perceived cyclic skin stretch for no mass added, 20g mass added, and 40g mass added testing conditions.

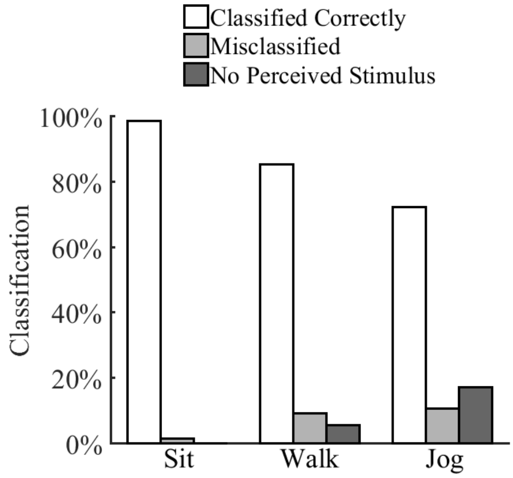


Figure 8. Overall classification results for sitting, walking, and jogging trials. "Classified Correctly" is the percentage of correctly perceived stimuli from the presented stimuli; "Misclassified" is the percentage of incorrectly perceived stimuli from the presented stimuli; and "No Perceived Stimulus" is the percentage of presented stimuli that were not perceived. The three presented stimuli that participants classified were 4 Hz, a location-dependent resonant frequency, and 30 Hz. Classified Correctly decreased and Misclassified and No Perceived Stimulus increased as the speed of movement increased.

was computed for all subjects across all frequencies. For each trial, all the percentages were smoothed via a 5-sample moving average filter and scaled by the maximum percentage value. Skin resonant frequencies for each condition were measured using the same methods described in Experiment I.

6.3 Results

In general, as device mass increased, the frequency range of the perceived cyclic skin stretch decreased (Fig. 7). Similarly, peak perceived cyclic skin stretch frequency was highest for the no mass condition and lowest for the largest (40g) mass added condition. Skin resonant frequencies mean (standard deviation) for the no mass added, 20g mass added and 40g mass added conditions were 14.3 (1.9), 11.8 (1.1), and 8.8 (0.9) Hz, respectively.

7 Experiment IV: Haptic Classification

Based on results from the two perceived haptic stimuli experiments, a fourth experiment was performed to determine whether subjects could differentiate distinct impact (4 Hz), cyclic skin stretch, and standard vibration (30 Hz) haptic cues while sitting, walking, and jogging.

7.1 Experimental Testing

Ten healthy subjects (ages 21-26, all male) without any adverse dermatological conditions or known sensory deficits participated in this study (same subjects as in the perceived haptic stimuli - different skin locations experiment), which was performed in accordance with the Declaration of Helsinki. Each subject performed one sitting, one walking, and one jogging trial while wearing the haptic device described in Section 2 at the forearm, shank, and foot, for a total of nine trials. The haptic device was taped to the skin via hypoallergenic, double-sided tape. All walking and jogging trials were performed on a treadmill (Bertec, Ohio, USA) at 1.2 m/s and 2.4 m/s, respectively.

During each trial, subjects were presented with a sequence of one of three haptic cues: distinct impact (4 Hz), cyclic skin stretch average resonance frequency for the given skin location from the skin resonance characterization experiment, or standard vibration (30 Hz). Haptic cues lasted 0.5 sec each and were presented in random order every 2 or 6 seconds. Each of the three haptic cues was presented five times during each trial. Subjects wore sound-blocking headphones to prevent potential detection of audio cues from the haptic device. During testing, subjects verbally reported each time they felt a haptic stimulus and simultaneously reported the type of stimulus. Verbal answers were recorded by a research staff member.

7.2 Data Analysis

Perceived haptic stimuli measured via subjects' verbal responses were compared with the actual presented haptic stimuli and the percentages of stimuli classified correctly, misclassified, and not perceived were computed for all subjects for the sitting, walking, and jogging conditions. In addition, confusion matrices were compiled for each type of trial (sitting, walking, jogging) and for each skin stimulus location (forearm, shank, foot).

7.3 Results

In general, the proportion of correctly classified haptic cues decreased while the proportion of misclassified and not perceived haptic cues increased with increasing speed of movement (Fig. 8). For sitting trials, 99% of haptic cues were correctly classified, only 1% of haptic cues were misclassified, and no haptic cues were not perceived. For walking, 85% of haptic cues were correctly classified, 9% were misclassified, and 6% were not perceived. And, for jogging, 72% of haptic cues were correctly classified, 11% were misclassified, and 17% were not perceived. Overall, subjects correctly classified 85%, misclassified 7%, and did not perceive 8% of all haptic cues for all trials.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TOH.2019.2917072, IEEE Transactions on Haptics

TABLE 1
Haptic Classification Confusion Matrices of Distinct Impact, Cyclic Skin Stretch and Standard Vibration Stimuli Presented on the Forearm, Foot, and Shank.

Presented Stimulus		Perceived Stimulus: Forearm				Foot				Shank			
		Distinct Impact	Cyclic Skin Stretch	Standard Vibration	Miss	Distinct Impact	Cyclic Skin Stretch	Standard Vibration	Miss	Distinct Impact	Cyclic Skin Stretch	Standard Vibration	Miss
Sit	Distinct Impact	98	2	0	0	96	4	0	0	94	6	0	0
Sit	Cyclic Skin Stretch	0	100	0	0	0	100	0	0	0	100	0	0
Sit	Standard Vibration	0	0	100	0	0	0	100	0	0	0	100	0
Walk	Distinct Impact	96	4	0	0	92	4	0	4	56	10	0	34
Walk	Cyclic Skin Stretch	0	98	2	0	6	90	4	0	14	68	10	8
Walk	Standard Vibration	0	2	98	0	0	0	100	0	0	26	70	4
Jog	Distinct Impact	90	2	0	8	74	2	0	24	10	10	0	80
Jog	Cyclic Skin Stretch	0	100	0	0	8	84	2	6	18	40	16	26
Jog	Standard Vibration	0	2	98	0	0	2	96	2	4	30	58	8

Note: 'Miss' means no stimulus was perceived.

Skin location was also a significant factor in subject ability to perceive and classify haptic cues (Table 1). The forearm and foot had noticeably higher overall correct classification rates (97% and 92%, respectively), than the shank (66%). Similarly, the overall misclassification and not perceived rates were much lower at the forearm (2% and 1%, respectively) and foot (4% and 4%, respectively) than at the shank (16% and 18%, respectively).

8 Discussion

This work introduced a new approach to haptic stimulation, resonant frequency skin stretch. This approach leverages the principle of resonant frequency to increase skin strain during stimulation.

Results from the skin resonance characterization experiment showed that skin on the foot had a significantly higher resonant frequency than skin on the shank or forearm (Fig. 3). This is likely because, based on mass-spring-damper modeling, the resonant frequency is inversely proportional to the square root of the moving mass, which includes device mass and mass of the moving skin, fat and muscle tissue at the point of haptic application. Muscle and fat tissue at the shank and forearm is larger than at the foot, which could account for the difference in resonant frequencies among those locations. In general, though, the resonant frequencies at the three skin locations were in roughly the same range (10-20 Hz).

In this study, the resonant frequency at each specific skin location was used in a haptic classification experiment at each respective location. It might also be possible to use an average skin resonant frequency activation across all three skin locations and get similar results if the activation frequency is close enough to the actual resonant frequency for each person and each skin location. This concept could also be potentially expanded and generalized to more skin locations across the body, though more detailed study is required. Also, given that skin elasticity and perception decrease with age [49], [50] and that we tested young adults, it is unlikely that resonant frequency findings in this study would generalize to older adults. Thus, further research should be performed to either heuristically determine resonant frequencies in skin for the presented wearable haptic device for specific age ranges for older adults, or a robust model should be developed and verified that accurately predicts skin resonant frequencies based on age.

It should also be noted that the skin's resonant frequency is directly related to the physical properties of the wearable haptic device used to impart the cyclic skin stretching actuations. Our study was for one particular implementation of resonant frequency skin stretch, and thus skin resonances estimated in this paper are specific to that device. Future work aimed at implementing resonant frequency skin stretch with other devices would thus result in different skin resonances. The weight of the wearable device will likely be the most important factor, with heavier devices resulting in lower skin resonant frequency and lighter devices resulting in higher resonant frequency. This is because, based on mass-spring-damper modeling, the resonant frequency is inversely proportional to the square root of moving mass of which the device mass would be a major contributor. The method of grounding the device could also influence the measured skin resonant frequency. In this paper, we taped the haptic device to the skin, and thus it was ungrounded and free to move with the skin. Grounding the haptic device to the body or fixed objects in the laboratory would also change the skin's effective resonant frequency.

Results from the perceived haptic stimuli experiment demonstrated that perception could be divided into three separate frequency ranges: at, above, and below the skin resonant frequency. Lower frequencies were perceived as distinct impacts and occurred roughly at or below 8 Hz, while higher frequencies were perceived as standard vibrations and occurred roughly at or above 28 Hz. "Distinct impacts" were perceived as distinct, likely because the time interval between impacts was larger at lower frequencies. Cyclic skin stretch feeling" were perceived as cyclic, likely because subjects felt their skin being stretched back and forth cyclically. This cyclic feeling was distinctly perceivable likely because the skin resonant frequencies (10-20 Hz) were not too high and the skin displacement was relatively large. In contrast with lower and middle (resonant) frequencies, distinct impacts and stretches were likely less distinguishable for higher frequencies and instead felt more like standard vibration sensations. Perceived direction of distinct impacts was not tested in this work, though it is likely that if the frequencies were low enough, users would be able to distinguish direction. This division of frequencies somewhat follows earlier research on vibrotactile stimulation showing a division in perception at about 10 Hz [21]. However, in that testing frequencies between 10-70 Hz were perceived as "flutter" and above 100 Hz were perceived as "smooth vibration". In our study, it is possible the perceived "standard vibrations" were more similar to "flutter", and that stimulation at the resonant frequency created a new type of haptic sensation not experienced in standard vibrotactile testing. Intermittent contacts during actuation could also further contribute to the perceived "flutter" sensation. The maximum stimulation frequency in our testing was 50 Hz, so it is also possible that higher frequency skin stretch testing could feel more and more "smooth". A detailed future study directly comparing perceived haptic stimuli with wearable skin stretch versus vibrotactile stimulation across a large spectrum of actuation frequencies could further illuminate these differences.

The transition phase from one perceived haptic stimuli to the next is somewhat gradual rather than sharp and distinct (Fig. 5). This is expected given that the relatively small resolution of frequencies (2 Hz) presented across multiple subjects should show variations. It may also be true that subjects mentally compare the current haptic skin stretch stimulation with the previous stimulation when assigning a perception. Thus, a higher resolution of presented stimulation frequencies and more possible options could create more opportunities to confuse perception on the current stimulation by comparing it with the previous stimulation. For example, if a subject first received a 34 Hz skin stretch and then a 30 Hz skin stretch, her perception of the 30 Hz skin stretch might be different than if she first received a 26 Hz skin stretch and then a 30 Hz skin stretch, because of the relative comparison and because the frequencies are relatively close. Skin stretch frequencies that are more widely separated and with fewer options would likely result in less confusion of perceived haptic stimuli for a given frequency. And this is in fact what was discovered in the fourth experiment, where only 3 possible skin stretch frequency stimulations were presented and classification accuracies were quite high for the sitting condition (Table 1). In addition, future research could explore the influence of human movement as an additional factor affecting the stimulus via a detailed analysis of the voice coil motion during walking and jogging.

Results from the haptic classification experiment revealed two important factors in classification accuracy: speed of movement and skin location. Overall, classification accuracy decreases from sitting to walking, and then decreases further from walking to jogging (Fig. 8). Correspondingly, misclassification and no perceived stimulus rates increase from sitting to walking, and then again from walking to jogging. These findings corroborate previous work showing that perceived haptic stimuli accuracy is lower when subjects walk or jog as compared to stationary tests [46], [51]. This may be due at least in part to the presence of skin, muscle, and fat tissue movement artifacts which occurs during walking, and especially during jogging that could cause extraneous haptic sensations potentially disrupting haptic stimulus perception and identification.

A closer look at the classification results shows that haptic skin location may be an even more important factor than movement speed. While there was an overall trend of increased movement speed accompanying a decrease in classification accuracy, this effect was minimal at the forearm, slightly more noticeable at the foot, and most pronounced at the shank (Table 1). For example, the classification accuracy at the forearm for sitting (99%) was almost unchanged for walking (97%) and jogging (96%). In contrast, the classification accuracy at the shank, while comparably high for sitting (98%), sharply dropped for walking (65%) and further sharply dropped again for jogging (36%). Similar trends were observed for increases in misclassification and not perceived stimulus rates based on skin location for the three movement speeds. This phenomenon may be due to the fact that extraneous haptic stimulations are more pronounced at the foot and shank during gait because the impact accelerations are larger there than at the forearm. The differing densities of mechanoreceptors in various skin locations [28] may also play a significant role in perception and could help explain why performance was higher in the foot (higher mechanoreceptor density) than the shank (lower receptor density), even though the extraneous stimulation is larger at the foot than shank during heel strikes. Additionally, it is possible that the extraneous stimulation from the repeated foot strikes during gait, which were near 4 Hz, contributed to the higher rate of "missed" haptic stimulations during walking and jogging for Distinct Impact stimulations. It is also possible that alignment of the actuator coil shaft with respect to the direction of impact force between the foot and ground could play a significant role in haptic perception and classification, particularly when the device is located on the shank for jogging applications, and thus future work should investigate this further. Walking and jogging could also affect user perception as these higher frequency movements could cause extraneous haptic stimulations from secondary device movements particularly during and immediately after heel strikes when the device is on the foot or shank. Further research is needed to determine

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TOH.2019.2917072, IEEE Transactions on Haptics

any contributions of secondary device movements on user perception for walking and jogging.

One direct implication of this work is that it could potentially enable widespread application of wearable skin stretch feedback for virtual and augmented reality. Current wearable skin stretch devices typically need to be "grounded" to the body by either strapping to a limb or the torso, but this implementation is in general not suitable for typically virtual and augmented reality applications, because of excess device bulk, which can quickly cause fatigue and discomfort. In contrast, the presented wearable skin stretch device should not be strapped to a limb or the torso, because it needs to move freely to leverage the skin resonant frequency effect. Rather, it is simply taped directly to the skin location of interest. This also opens the possibility to provide wearable skin stretch feedback in skin locations not accessible by existing devices that require strapping; for example, the upper shoulder, center of the upper back, and back of neck are all locations where it is either not possible or would be uncomfortable to strap a wearable skin stretch device, but that would be relatively straight-forward to tape the presented wearable device. Though it is beyond the scope of this paper to perform and present a thorough analysis, it is also likely that the size, weight, cost, and power requirements of the presented wearable device are also significantly less than existing wearable skin stretch devices, further improving the potential suitability of widespread implementation.

Non-glabrous skin was the target for resonant frequency skin stretch in this study, and future work could consider extending this concept to the glabrous skin of the fingers and hands. For example, resonant frequency skin stretch applied laterally at the fingertip or along the skin of the finger could potentially enable new cutaneous and kinesthetic stimuli sensations [27]. Also, while in this study resonant frequency skin stretch was applied laterally to the skin, it may be possible to apply the same principle to normal skin indentation to create similar or related effects.

Haptic illusions could also potentially be created or strengthened by implementing resonant frequency skin stretch. For example, asymmetric vibrations have been applied to the skin of the fingers and hands to create pulling sensations, giving the illusion of two-dimensional or three-dimensional forces from ungrounded devices [36], [37]. It is possible that targeting the skin's resonant frequency during asymmetric stimulation could strengthen this illusion. Resonant frequency skin stretch could also be explored to create or enhance a host of other tactile and haptic illusions involving texture, stiffness, weight, density, shape, size, or body space [26]. Additionally, while this paper emphasized the novelty of resonant frequency skin stretch, it would also be possible to reframe this work as a study of three haptic icons: low frequency, middle (resonant) frequency, and high frequency and the ability to distinguish between them in different testing scenarios.

A limitation of this study is that only three specific movement speeds (standing, walking at 1.2 m/s, and jogging at 2.4 m/s) were tested at three specific skin locations (forearm, foot, and shank). Testing more movement speeds would provide a clearer picture of the relationship between ambulation speed and perceived haptic stimuli for the wearable haptic device. Similarly, testing more skin locations would provide further insights into how generalizable these findings are across the body.

In conclusion, we presented a novel approach to wearable haptic stimulation that targets lateral stretch of the skin at the skin's resonant frequency. An initial experiment showed that skin resonant frequencies at the forearm, shank, and foot while wearing the device were in the 10-20 Hz range. A follow-up study demonstrated that subjects perceived stimulations at, above, and below the skin's resonant frequency differently, i.e. lower frequency stimuli felt like distinct impacts, resonant frequency stimuli felt like cyclic skin stretches, and high frequency stimuli felt like standard vibrations. In the final experiment, subjects were able to use the wearable haptic skin stretch device to classify haptic stimulations while sitting, walking, and jogging. Classification accuracy decreased with increasing speed, especially for haptic stimulations at the shank. This work could serve to facilitate more widespread use of wearable skin stretch and seems particularly promising as a haptic feedback modality for virtual and augmented reality, such as for gaming, in medical training simulations and surgical augmentation, and for training to improve sports performance or prevent injuries.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (51875347) and the U.S. National Science Foundation (1830163).

REFERENCES

[1] I. Choi, H. Culbertson, M. R. Miller, A. Olwal, and S. Follmer, "Grabity: A Wearable Haptic Interface for Simulating Weight and Grasping in Virtual Reality," *Proc. 30th Annu. ACM Symp. User interface Softw. Technol. - UIST '17*, 2017.

[2] K. Minamizawa, S. Fukamachi, H. Kajimoto, N. Kawakami, and S. Tachi, "Gravity grabber: wearable haptic display to present virtual mass sensation," *ACM SIGGRAPH 2007 Emerg. Technol.*, p. 8, 2007.

[3] P. B. Shull and D. D. Damian, "Haptic wearables as sensory replacement, sensory augmentation and trainer – a review," *J. Neuroeng. Rehabil.*, vol. 12, no. 1, p. 59, 2015.

[4] J. Wheeler, K. Bark, J. Savall, and M. Cutkosky, "Investigation of rotational skin stretch for proprioceptive feedback with application to myoelectric systems.," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 18, no. 1, pp. 58–66, Feb. 2010.

[5] K. Bark, J. Wheeler, P. B. Shull, J. Savall, and M. Cutkosky, "Rotational skin stretch feedback: a wearable haptic display for motion," *IEEE Trans. Haptics*, vol. 3, no. 3, pp. 166–176, 2010.

[6] K. O. Johnson, "The roles and functions of cutaneous mechanoreceptors," *Curr. Opin. Neurobiol.*, vol. 11, no. 4, pp. 455–461, 2001.

[7] R. S. Johansson and G. Westling, "Roles of glabrous skin

receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects," *Exp. Brain Res.*, vol. 56, no. 3, pp. 550–564, Oct. 1984.

[8] Z. F. Quek *et al.*, "Augmentation of stiffness perception with a 1-degree-of-freedom skin stretch device," *IEEE Trans. Human-Machine Syst.*, vol. 44, no. 6, pp. 731–742, 2014.

[9] W. R. Provancher and N. D. Sylvester, "Fingerpad Skin stretch increases the perception of virtual Friction," *IEEE Trans. Haptics*, vol. 2, no. 4, pp. 212–223, 2009.

[10] S. J. Bensmaïa, Y. Y. Leung, S. S. Hsiao, and K. O. Johnson, "Vibratory Adaptation of Cutaneous Mechanoreceptive Afferents," *J. Neurophysiol.*, vol. 94, no. 5, pp. 3023–3036, Nov. 2005.

[11] S. Okamoto, M. Konyo, and S. Tadokoro, "Vibrotactile Stimuli Applied to Finger Pads as Biases for Perceived Inertial and Viscous Loads," *IEEE Trans. Haptics*, vol. 4, no. 4, pp. 307–315, Oct. 2011.

[12] R. W. Cholewiak, A. A. Collins, and J. C. Brill, "Spatial factors in vibrotactile pattern perception," in *Eurohaptics*, 2001, pp. 41–48.

[13] H. Culbertson, S. B. Schorr, and A. M. Okamura, "Haptics : The Present and Future of Artificial Touch Sensations," *Annu. Rev. Cont. Rob., Aut. Sys*, vol. 1, pp. 385–409, 2018.

[14] S. Choi and K. J. Kuchenbecker, "Vibrotactile display: Perception, technology, and applications," *Proc. IEEE*, vol. 101, no. 9, pp. 2093–2104, 2013.

[15] R. S. Johansson and J. R. Flanagan, "Coding and use of tactile signals from the fingertips in object manipulation tasks.," *Nat. Rev. Neurosci.*, vol. 10, no. 5, pp. 345–59, May 2009.

[16] K. Johnson, T. Yoshioka, and F. Vega-Bermudez, "Tactile functions of mechanoreceptive afferents innervating the hand," *J Clin. Neurophysiol.*, vol. 17, no. 6, pp. 539–558, 2000.

[17] E. B. Goldstein, *Sensation and Perception*, 6th ed. Pacific Grove, CA: Wadsworth-Thomson Learning, 2002.

[18] L. A. Jones and N. B. Sarter, "Tactile Displays: Guidance for Their Design and Application," *Hum. Factors J. Hum. Factors Ergon. Soc.*, vol. 50, no. 1, pp. 90–111, Feb. 2008.

[19] B. B. Edin, "Quantitative Analyses of Dynamic Strain Sensitivity in Human Skin Mechanoreceptors," *J. Neurophysiol.*, vol. 92, no. 6, pp. 3233–3243, 2004.

[20] A. Guzererler, W. R. Provancher, and C. Basdogan, "Perception of skin stretch applied to palm: Effects of speed and displacement," *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, vol. 9774. pp. 180–189, 2016.

[21] H. Z. Tan, N. I. Durlach, C. M. Reed, and B. Rabinowitz, "Information transmission with a multifinger tactual display," *Percept. Psychophys.*, vol. 61, no. 6, pp. 993–1008, 1999.

[22] J. Ryu, J. Jung, G. Park, and S. Choi, "Psychophysical model for vibrotactile rendering in mobile devices," *Presence Teleoperators Virtual Environ.*, vol. 19, no. 4, pp. 1–24, 2010.

[23] R. Ackerley, I. Carlsson, H. Wester, H. Olausson, and H. B. Wasling, "Touch perceptions across skin sites: Differences between sensitivity, direction discrimination and pleasantness," *Front. Behav. Neurosci.*, vol. 8, p. 54, 2014.

[24] B. L. Whitsel *et al.*, "Dependence of Subjective Traverse Length on Velocity of Moving Tactile Stimuli," *Somatosens. Res.*, vol. 3, pp. 185–196, 1986.

[25] R. W. Cholewiak, "The perception of tactile distance: Influences of body site, space, and time," *Perception*, vol. 28, no. 7, pp. 851–875, 1999.

[26] S. J. Lederman and L. A. Jones, "Tactile and Haptic Illusions," *IEEE Trans. Haptics*, vol. 4, no. 4, pp. 273–294, 2011.

[27] C. Pacchierotti, S. Sinclair, M. Solazzi, A. Frisoli, V. Hayward, and D. Prattichizzo, "Wearable Haptic Systems for the Fingertip and the Hand: Taxonomy, Review, and Perspectives," *IEEE Trans. Haptics*, vol. 10, no. 4, pp. 1–1, 2017.

[28] S. J. Bolanowski, G. A. Gescheider, and R. T. Verrillo, "Hairy skin: Psychophysical channels and their physiological substrates," *Somatosens. Mot. Res.*, vol. 11, no. 3, pp. 279–290, 1994.

[29] B. T. Gleeson, S. K. Horschel, and W. R. Provancher, "Perception of direction for applied tangential skin displacement: Effects of speed, displacement, and repetition," *IEEE Trans. Haptics*, vol. 3, no. 3, pp. 177–188, 2010.

[30] A. L. Guinan, N. A. Caswell, F. A. Drews, and W. R. Provancher, "A video game controller with skin stretch haptic feedback," in *IEEE International Conference on Consumer Electronics (ICCE)*, 2013, pp. 456–457.

[31] A. L. Guinan, N. C. Hornbaker, M. N. Montandon, A. J. Doxon, and W. R. Provancher, "Back-to-back skin stretch feedback for communicating five degree-of-freedom direction cues," in *IEEE World Haptics Conference*, 2013, pp. 13–18.

[32] A. Girard, M. Marchal, F. Gosselin, A. Chabrier, F. Louveau, and A. Lécuyer, "HapTip: Displaying Haptic Shear Forces at the Fingertips for Multi-Finger Interaction in Virtual Environments," *Front. ICT*, vol. 3, no. April, 2016.

[33] S. B. Schorr and A. M. Okamura, "Three-Dimensional Skin Deformation as Force Substitution: Wearable Device Design and Performance during Haptic Exploration of Virtual Environments," *IEEE Trans. Haptics*, vol. 10, no. 3, pp. 418–430, 2017.

[34] C. J. Ploch, J. Hwa, B. Wendy, and M. Cutkosky, "Haptic Skin Stretch on a Steering Wheel for Displaying Preview Information in Autonomous Cars," in *IEEE International Conference on Intelligent Robots and Systems (IROS)*, 2016, pp. 60–65.

[35] Y. Pan and P. Hur, "Interactive Balance Rehabilitation Tool with Wearable Skin Stretch Device," in *IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*, 2017, pp. 489–494.

[36] H. Culbertson, J. M. Walker, M. Raitor, and A. M. Okamura, "WAVES: A Wearable Asymmetric Vibration Excitation System for Presenting Three-Dimensional Translation and Rotation Cues," *Proc. 2017 CHI Conf. Hum. Factors Comput. Syst. - CHI '17*, pp. 4972–4982, 2017.

[37] T. Amemiya and H. Gomi, "Active Manual Movement Improves Directional Perception of Illusory Force," *IEEE Trans. Haptics*, vol. 9, no. 4, pp. 465–473, 2016.

[38] V. Yem and H. Kajimoto, "Wearable tactile device using mechanical and electrical stimulation for fingertip

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TOH.2019.2917072, IEEE Transactions on Haptics

interaction with virtual world," in *2017 IEEE Virtual Reality (VR)*, 2017, pp. 99–104.

[39] F. Chinello, C. Pacchierotti, J. Bimbo, N. G. Tsagarakis, and D. Prattichizzo, "Design and evaluation of a wearable skin stretch device for haptic guidance," *IEEE Robot. Autom. Lett.*, vol. 3, no. 1, pp. 1–1, 2017.

[40] H. U. Yoon, N. Anil Kumar, and P. Hur, "Synergistic Effects on the Elderly People's Motor Control by Wearable Skin-Stretch Device Combined with Haptic Joystick," *Front. Neurorobot.*, vol. 11, no. June, pp. 1–20, 2017.

[41] P. B. Shull, K. Lurie, M. R. Cutkosky, and T. Besier, "Training multi-parameter gaits to reduce the knee adduction moment with data-driven models and haptic feedback," *J. Biomech.*, vol. 44, no. 8, pp. 1605–1609, 2011.

[42] D. K. Y. Chen, I. A. Anderson, C. G. Walker, and T. F. Besier, "Lower Extremity Lateral Skin Stretch Perception for Haptic Feedback," *IEEE Trans. Haptics*, vol. 9, no. 1, pp. 62–68, Jan. 2016.

[43] K. Bark, J. W. Wheeler, S. Premakumar, and M. R. Cutkosky, "Comparison of Skin Stretch and Vibrotactile Stimulation for Feedback of Proprioceptive Information," *2008 Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst.*, pp. 71–78, Mar. 2008.

[44] N. A. Caswell, R. T. Yardley, M. N. Montandon, and W. R. Provancher, "Design of a forearm-mounted directional skin stretch device," *Haptics Symp. 2012, HAPTICS 2012 - Proc.*, pp. 365–370, 2012.

[45] A. Ion, E. J. Wang, and P. Baudisch, "Skin Drag Displays: Dragging a Physical Tactor across the User's Skin Produces a Stronger Tactile Stimulus than Vibrotactile," *Proc. 33rd Annu. ACM Conf. Hum. Factors Comput. Syst. - CHI '15*, no. c, pp. 2501–2504, 2015.

[46] W. J. Jirattigalachote, P. B. Shull, and M. R. Cutkosky, "Virtual pebble: a haptic state display for pedestrians," in *IEEE Ro-Man Symposium*, 2011, pp. 401–406.

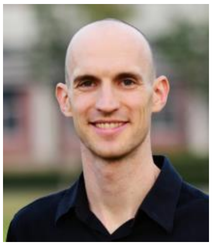
[47] "ISO-7626/1-5: Vibration and Shock – Experimental Determination of Mechanical Mobility," *Int. Stand. Organ.*, 1994.

[48] J. Canny, "A Computational Approach to Edge Detection," *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. PAMI-8, no. 6, pp. 679–698, 1986.

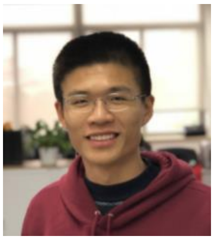
[49] A. Cua, K. Wilhelm, and H. Maibach, "Elastic properties of human skin: relation to age, sex, and anatomical region," *Arch. Dermatol. Res.*, vol. 282, no. 5, pp. 283–288, 1990.

[50] S. W. Shaffer and A. L. Harrison, "Aging of the Somatosensory System: A Translational Perspective," *Phys. Ther.*, vol. 87, no. 2, pp. 193–207, Feb. 2007.

[51] A. Meier, D. J. C. Matthies, B. Urban, and R. Wettach, "Exploring vibrotactile feedback on the body and foot for the purpose of pedestrian navigation," in *Proceedings of the 2nd international Workshop on Sensor-based Activity Recognition and Interaction - WOAR '15*, 2015, pp. 1–11.



Peter B. Shull received the B.S. in Mechanical Engineering and Computer Engineering from LeTourneau University in 2005 and M.S. and Ph.D. degrees in Mechanical Engineering from Stanford University in 2008 and 2012, respectively. From 2012 to 2013, he was a postdoctoral fellow in the Bioengineering Department of Stanford University. He is currently an Associate Professor in Mechanical Engineering at Shanghai Jiao Tong University. His research interests include wearable systems, real-time movement sensing and feedback, gait retraining, and biomechanics.



Tian Tan received the B.S. degree in Mechanical Engineering from Nanjing University of Science & Technology in 2016. He is currently pursuing the Ph.D. degree with the State Key Laboratory of Mechanical System and Vibration, School of Mechanical Engineering, at Shanghai Jiao Tong University. His research interests include haptic feedback, wearable systems, and machine learning for inertial motion sensing.

Heather Culbertson received the B.S. from the Department of Mechanical Engineering at the University of Nevada, Reno in 2010, and the M.S. and PhD. degrees from the Department of Mechanical Engineering and Applied Mechanics at the University of Pennsylvania in 2013 and 2015, respectively. She is currently the WiSE Gabilan Assistant Professor of Computer Science and Aerospace and Mechanical Engineering at the University of Southern California. Her research interests include haptics, human-computer interaction, and human-robot interaction.

Xiangyang Zhu received the B.S. degree from the Department of Automatic Control Engineering, Nanjing Institute of Technology, Nanjing, China, in 1985, the M.Phil. degree in instrumentation engineering and the Ph.D. degree in automatic control engineering, both from Southeast University, Nanjing, China, in 1989 and 1992, respectively. From 1993 to 1994, he was a Postdoctoral Research Fellow with the Huazhong University of Science and Technology, Wuhan, China. In 1995, he joined the Department of Mechanical Engineering, Southeast University, as an Associate Professor. Since June 2002, he has been with the School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai, China, where he is currently a Changjiang Chair Professor and the Director of the Robotics Institute. His current research interests include robotic manipulation planning, human-machine interfacing, and biomechatronics.

Allison M. Okamura received the B.S. degree from the University of California, Berkeley, in 1994, and the M.S. and Ph.D. degrees from Stanford University, Stanford, CA, in 1996 and 2000, respectively, all in mechanical engineering. She is currently a Professor of mechanical engineering at Stanford University, Stanford, CA. Her research interests include haptics, teleoperation, medical robotics, virtual environments and simulation, neuromechanics and rehabilitation, soft robotics, and engineering education.