Force Jacket: Pneumatically-Actuated Jacket for Embodied Haptic Experiences

Alexandra Delazio* **Ken Nakagaki†*** **Roberta Klatzky‡** **Scott E. Hudson‡***
Jill Fain Lehman* **Alanson Sample***

*Disney Research, Pittsbrugh, PA
†MIT Media Lab, Cambridge, MA
‡Carnegie Melon University, Pittsburgh, PA

*{alexandra.delazio, jill.lehman, alanson.sample}@disneyresearch.com,
†ken_n@media.mit.edu, ‡klatzky@cmu.edu, scott.hudson@cs.cmu.edu

ABSTRACT
Immersive experiences seek to engage the full sensory system in ways that words, pictures, or touch alone cannot. With respect to the haptic system, however, physical feedback has been provided primarily with handheld tactile experiences or vibration-based designs, largely ignoring both pressure receptors and the full upper-body area as conduits for expressing meaning that is consistent with sight and sound. We extend the potential for immersion along these dimensions with the Force Jacket, a novel array of pneumatically-actuated airbags and force sensors that provide precisely directed force and high frequency vibrations to the upper body. We describe the pneumatic hardware and force control algorithms, user studies to verify perception of airbag location and pressure magnitude, and subsequent studies to define full-torso, pressure and vibration-based feel effects such as punch, hug, and snake moving across the body. We also discuss the use of those effects in prototype virtual reality applications.

ACM Classification Keywords
H.5.2 User Interfaces: Haptic I/O, Interaction Styles

Author Keywords
Haptics; Pneumatic Actuation; Force Feedback; Vibrotactile; Wearable; Virtual Reality

INTRODUCTION
The creation of immersive virtual and augmented realities relies on engaging all of the senses. Although the fields of visual effects and sound effects have long histories and a wide variety of technologies to contribute, the inclusion of haptic feedback in such experiences is an area of recent growth. Many of the new haptic technologies being explored focus on feedback to the hand [4], fingertip[3], and hand-held tools[19]. However, as VR and AR applications increasingly expand to full-body

CHI 2018, April 21–26, 2018, Montreal, QC, Canada

ISBN 978-1-4503-5620-6/18/04...$15.00

DOI: https://doi.org/10.1145/3173574.3173894

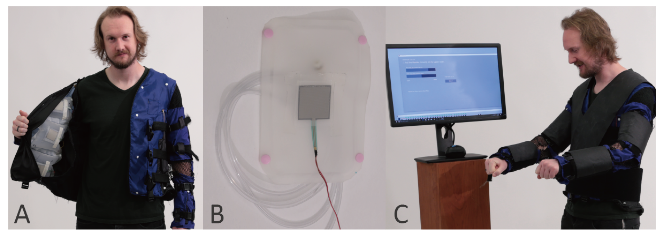


Figure 1. Force Jacket - A: Appearance of Force Jacket; B: Individual airbag with force sensitive resistor; C: User study set-up.

spatial experiences, tactile sensation must expand with them. Similarly, most current approaches are limited to expressing motion and vibrational feedback through vibrotactile stimulation [11, 12, 13], ignoring the role of sustained or distributed force in conveying realism. Even in the real world, very few experiences are conveyed by vibration alone.

To move toward more expressive technology, a wearable haptic interface, the Force Jacket, that has both vibrotactile and variable force feedback for the upper body and arms was introduced (Figure 1A). A software-controlled valve system inflates and deflates each of 26 bags independently to provide targeted forces and vibrotactile stimulation against each part of the upper body relative to force sensitive resistors on each bag (Figure 1B). An initial user study evaluated users' perception of airbag localization and magnitude where users experienced seven levels of pressure (1.6 - 8.5 N) on 26 upper body locations, generating a perceptually reliable range of values (Figure 1C). The values formed the basis for a second study in which users authored *feel effects* such as punch, hug, and a snake moving across the body, based on the paradigm in [12]. Finally, we derive canonical values from the user-authored data for a subset of the feel effects to demonstrate the capability of the Force Jacket in several applications.

Contributions of this work include:

- A pneumatic haptic wearable system based on the combination of airbags and force sensitive resistors
- Hardware and control algorithms capable of generating both strong static pressures on the body as well as high frequency vibrations (similar to vibration motors) with the airbags

- Studies to measure users' perception of haptic actuation from airbags in terms of localization and magnitude
- Conducted user studies to generate a library of fourteen feel effects based on pressure and vibrotactile stimulation that correspond with language phrases for physical interactions such as tap, rain, hug, etc.
- Demonstrated utility of the Force Jacket to enhance virtual reality experiences

RELATED WORK

Haptic applications aim to create immersive virtual experiences, provide active feedback and notification, and emulate the shape and texture of digital objects. We will not attempt to review the entire field, but instead highlight a few areas of closest relevance to the work presented here.

On-body Haptic Interfaces

With affordable VR headsets becoming readily available, on-body haptic feedback has become an increasingly attractive area of research. Researchers have taken several different approaches to enhance the strong visual and spatial effects of Virtual Reality (VR) by allowing users to experience physical haptic feedback on the body.

Haptic systems traditionally make use of vibrotactile mechanisms. One research group produced the Synesthesia Suit which utilizes 26 vibrotactile actuators on a full-body suit for enhancing VR gaming experiences [13]. Researchers have also shown that arrays of vibrotactile actuators can provide perception of smooth motion on the back [11]. Vibrotactile wearable systems have also been broadly used for non-VR applications such as to aid navigation for the blind [23], and affective interfaces [2].

Electro Muscle Stimulation (EMS) is another increasingly popular approach for haptic VR experiences. EMS directly stimulates muscles with electric impulses to elicit muscle contraction, thus activating body motion. As for VR interfaces, Lopes et al. introduced this technique to elicit a sensation of touching virtual object [17]. Unlimited Hand is a commercial mobile device worn on the wrist for this same purpose [9].

While these approaches effectively provide specific haptic feedback such as vibration and kinetic body motion, they do not exert force, pressure, or compression onto the body similar to that of a push or hug. The aim of the research in this paper was to develop a pneumatically-actuated general platform for on-body haptic feedback, and to explore haptic effects that can be better created with pneumatic actuation.

Pneumatic Interfaces

Recently pneumatic actuation technology has been a popular choice for enabling soft, shape changing interfaces for tangible and haptic interactions. Various fabrication techniques have been introduced such as molding and casting silicone [34], heat sealing textiles [21] and 3D printing soft materials [32]. Vázquez et al. also explored variable force feedback by combining air pressure sensors with 3D printed inflatable structures [32]. Another project developed this approach, called Pneumatibles, with a single pneumatically driven actuator that simulated a button. A novel control system decoupled the air-supply from the actuator. Time-varying pressure sequences were implemented to create discriminable tactile patterns (with some error), as confirmed in a user study [7].

Research has also concerned pneumatically actuated on-body haptic interfaces. He et al. presented PneuHaptic which is an armband-shaped haptic interface with an array of small airbags for providing haptic feedback[10]. Frozen Suit is a full-body haptic interface which hardens the joints on the limbs with a jamming technique in order to create an experience of a frozen body in VR games[1]. Similar to our system, PHANTOM-SENSE is a commercial pneumatic haptic vest for enhancing gaming experience by providing haptic feedback on the upper body [5]. A series of studies by Pohl et al. demonstrated that on-limb pneumatic compression feedback can be used for notification [24] as well as inhibition of body motion [25], by means of a closed-loop control system using air pressure sensors and commercial blood pressure cuffs. Additionally, on-body pneumatic feedback systems are utilized to reproduce various experiences such as being hugged [29, 30], or being pregnant (feeling a baby kick) [14].

The Force Jacket system differs from previous research applications in several ways: 1. An airbag control system with closed loop control using force sensitive resistors was implemented; 2. Instead of using vibrotactile motors, rapid actuation and variable activation pressure was supported using both compressed air and vacuum sources; 3. User studies were conducted to define effects based on users' sensory expectations.

Perceptual User Studies with Haptics

In contrast to the large body of research on basic sensory functions of the haptic system, there is relatively little research on the semantics of haptic effects, i.e., how they create meaning. One approach is to work within verbal language and identify terms that relate to tactile sensation or emotional arousal [8]. A more direct approach is to use stimulation within the perceptual domain of touch and evaluate affective responses. For example, one study investigated the parameters that make brief tactile clicks pleasant [15].

O'Sullivan and Chang [22] noted the need for a language that could describe vibrotactile stimuli in meaningful terms, as opposed to sensation descriptors like "buzz". Their approach, based on families of noise described by Russolo [26], identified vibratory families like "quakes", "beats" or "living" (e.g., resonance in your chest). Another acoustically-motivated approach transformed music into tactile stimulation and extracted dimensions of intrusiveness and tempo [31].

A variety of tactile icons have been developed using simple actuators. The emotional content conveyed by amplitude, frequency, duration, and envelope was scaled within dimensions of valence (positive/negative) and arousal [36]. MacLean and collaborators have extensively studied the communicative function of haptic icons [18]. Other work by this group has developed a "haptic creature" that senses touch and expresses the affective response in other modalities [35].

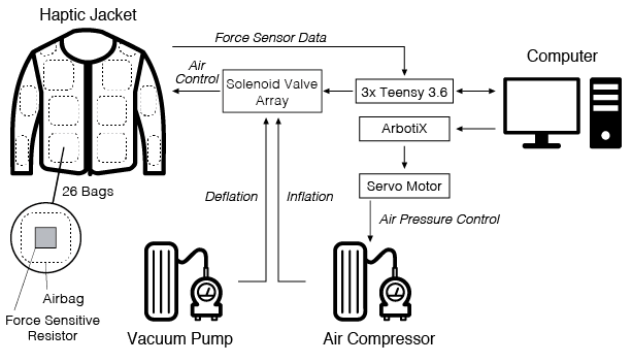


Figure 2. Overview of the Force Jacket system.

Figure 3. Force Jacket with internal airbags layout exposed.

Israr et al. defined a *feel effect* (FE) as an explicit pairing between a meaningful linguistic phrase and a rendered haptic pattern [12], and a methodology for generating FEs from non-technical users by priming sense memory. Although that work explored the relationship between semantics and haptics only for vibrotactile phenomena, we emulate the experimental paradigm in our second study, extending the original theory into the pressure domain.

IMPLEMENTATION

The haptic Jacket consists of 26 air compartments each equipped with force sensitive resistors. A compressor supplies air to each compartment through individually controlled solenoid valves. A vacuum pump, also connected to the bags via solenoids, allows for quick air removal. The actuation of the airbags is controlled by three Teensy 3.6 microcontrollers (See Figure 2). The intention for the overall system is to present a novel haptic embodied experience by means of a prototype of multi-area pneumatic force feedback. At this stage of work, the goal is to develop core technology for the Force Jacket that will be sufficient for basic psychophysical assessment and to design and test an initial set of effects. Further development to improve the technology will occur in follow-on stages of the project, based on the results of the studies reported here.

Force Jacket Design

Wearable Design

The haptic wearable was designed as a vest with adjustable sleeves to comfortably fit a wide range of user body types with varying heights and weights. The vest portion of the Jacket was a re-purposed life vest with the inner flotation foam removed and replaced with air compartments. Jacket sleeves were created using a combination of ripstop nylon and mesh materials. Velcro was attached to the arms and body of the Jacket to ensure secure fit on users. The Jacket with all tubing and air compartments attached weighed about 5 lbs.

Air Compartment Design

Twenty-six airbags were installed throughout the Jacket. This density was sufficient to implement the sense of motion across the upper-body from one bag to another, while also ensuring that the jacket tubing was not too bulky. Figure 3 highlights the airbags' allocation: six air compartments on the front of the body, six on the back of the body, two on either side of the body, and four on each arm. Each air compartment was made from a 0.015" thick polyurethane film and fabricated using a custom built three-axis CNC heat-sealing machine, inspired by the aeroMorph device described in [21]. Zippers were installed inside of the wearable to allow for easy access to all airbags. A 1.5"x1.5" square force sensitive resistor (FSR) was placed in a pocket on each of the airbags on the inside of the jacket facing the body surface.

Pneumatic Control

Ten feet of PVC tubing (1/8" ID, 1/4" OD) was attached to each of the air compartments and routed through the wearable to the outlet ports of 26 corresponding solenoid valve manifolds (Clippard EFB-2DV-12-L, 5-10 ms response time). These manifolds consisted of two 2-way solenoid valves that share an outlet port. One solenoid valve on the manifold was connected via PVC tubing to an air compressor (Rolair JC10 - 1725 RPM) while the other was connected to a vacuum (Welch Vacuum 2585B-50 - 201 LPM) (Figure 4). Solenoid valves were controlled on and off to accumulate and release air to and from the air compartments according to commands programmed into three Teensy 3.6 micro-controllers. The air pressure with which the compressed air was released from the air compressor was automatically adjusted using a servomotor controlled by an Arbotix micro controller.

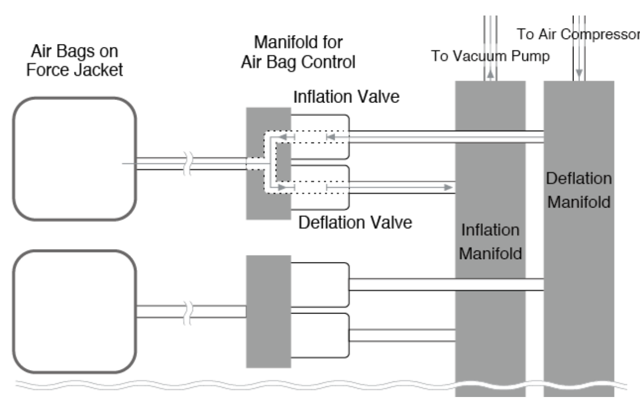


Figure 4. Schematic of airbag tubing. (Airflow denoted by arrows)

Airbag Actuation

Basic Airbag Control for Force Feedback

A basic control algorithm that was programmed onto Teensy 3.6 microcontrollers controlled each airbag to reach target force [N] that would be dynamically adjusted from other software on a computer. When the actual force detected from the FSR on the bag was lower than the target force, it would inflate, and vice versa. A target range was defined to be 0.5 N as an offset, so that the system held the air for the bags if the FSR values were within the target range. Additionally, because the force sensor value from FSRs can dynamically change when subjects breath or move their body, the control algorithm was designed not to inflate/deflate when target force was not being updated from the computer.

The range of force values applied to the body was set to be between 0 - 9.0N. As the minimum force that FSR could detect was 0.3N, the actual range of the force the system can control is higher than 0.3N. A preliminary test was conducted to observe the relationship between the target force value sent from the computer and actual force value read from the FSR. With this basic force control algorithm, preliminary measurement was conducted to compare the input target force value specified from the software and output actual force value detected by the FSR on each airbag. These measurements were simulated on mannequins across four different body types (male, female with large and small sizes for each) with two types of force changing standing wave (square wave and sine wave). Figure 5 shows an example graph of comparison between target force and detected force for a single kind of mannequin with two wave types. With the air compressor pressure set to approximately 40 psi, the target force value and detected force value matched with a delay under 0.8 seconds (to switch between 1.5N to 5.5N) and pressure error under 1.5N.

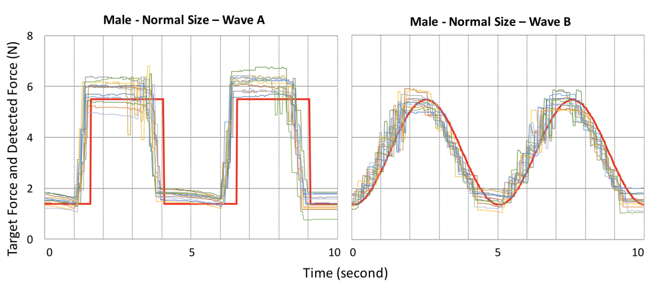


Figure 5. Example graphs of initial test for the force control algorithm. The red thick line represents the target force value and other thin lines represent detected force values from each airbag's FSR.

Fluttering Control for Vibrotactile Feedback

In addition to the simple algorithm to reach target force by inflating/deflating the airbags, another control method was developed to create a fluttering effect. The aim of this control was to create vibration haptic effects *similar* to those created using a vibrotactile motor based designs. While a pneumatic system cannot achieve the range and precision of frequency obtainable with a vibrotactile actuator, it can produce a unique haptic effect by which force and vibration (up to 40Hz) are controlled at the same time.

This control system was designed in the way that computer software sends a frequency value to generate fluttering effects. When each Teensy received specific frequency values for airbags, the Teensy switches the corresponding solenoid valves with the target frequency in three different ways depending on the target force and actual force value from the FSR; switch between Inflate and Hold when the bag is inflating to increase force, Inflate and Deflate when the bag is in target range, and Hold and Deflate when decreasing the force. The solenoid valves used allowed the system to create a fluttering effect up to 40Hz.

The ability of the pneumatic system to control both the force/pressure exerted by each bag as well as the vibrational tendency of the bags allowed the overall system to operate in two different modes: *Force Mode* (bag strictly exerts a force between 0.3 and 9N) and *Vibration Mode* (bag can create a vibrotactile effect with a frequency up to 40Hz in addition to the force).

BASIC PERCEPTION USER STUDIES

Localization and Magnitude perception user studies were performed to characterize the psychophysics of the haptic pneumatic system.

For both sets of studies, users were asked to wear the Force Jacket and stand (or sit if preferred) 36 inches away from a computer monitor. Facing the monitor, they used their right hand to control a mouse for responses. Experimenters monitored and controlled the pneumatic system behind the subjects as shown in Figure 1C. Participants (N = 16, 8 female, 8 male), aged 18-60 (M = 26.07, SD = 3.58) were recruited for these studies and received 15 dollars as compensation. Two user studies were conducted in a row which lasted approximately 40 - 60 minutes total, including 5 minutes break in-between.

Localization User Study

The aim of the first psychophysical study was to determine users' ability to perceive the location of the various inflatable compartments in the haptic pneumatic wearable.

Procedure

To determine users' perception of inflation location, a single compartment within the wearable was inflated and deflated. Immediately following deflation, subjects were shown a human figure on the screen and asked to click on the location where they felt pressure. All 26 compartment locations were tested in random order within each of two successive blocks. The x and y coordinates of the subjects' responses were recorded.

Results

Target locations, in terms of x and y coordinates, were used to determine the actual precise position of each airbag within the haptic wearable. For each of the 26 locations, each of the subjects' two responses were averaged. The difference between their response coordinates and the target location coordinates was determined. The centroid was then calculated by taking the mean x and y responses across all subjects for that location. The average bias was determined by taking the difference between the target location and the mean of x and y responses across all subjects. The standard deviation was calculated in the x and y directions to measure the precision (inverse of noise) in users' perceived location (See Figure 6.) The arm locations were combined into right and left upper arm and lower arm categories, averaging over front and back responses. (There was apparent ambiguity of these terms, as the arm can be rotated to move the palm to parallel the front or back of the body.)

Discussion

All pressure sites were easily localized by subjects within the boundaries of the airbag locations as shown in Figure 6. It can be seen that the centroids of responses lie within the appropriate bag boundary, and a 1-standard-deviation error tends not to cross over the boundary. Exceptions indicate small but systematic biases. For example, there was a tendency to feel the lower arm location toward the wrist. Shoulder locations were biased toward the upper back rather than centered on top of the shoulders. Lastly, there was a bias for users to perceive the mid front compartments above the bag midline. These biases may reflect the Jacket design and fit, biases in people's mental body image, or low-level sensory phenomena. These results indicate considerable promise for the use of a pneumatic upper-body haptic interface and also suggest design guidelines. The accuracy of localization sets at least a lower bound on the possible density of sites that can be stimulated without spatial confusion. It is possible that more dense placement could be achieved by using smaller bags; however, further perceptual studies would be needed to confirm the precision of localization. Given confirmation of the ability to feel distinct individual bag locations, a series of more complex haptic sensations could be developed. The study also points to biases that could be compensated for by bag placement. For example, to compensate for the perceptual displacement of the lower arm toward the wrist, the corresponding bag should be moved by a commensurate amount toward the elbow.

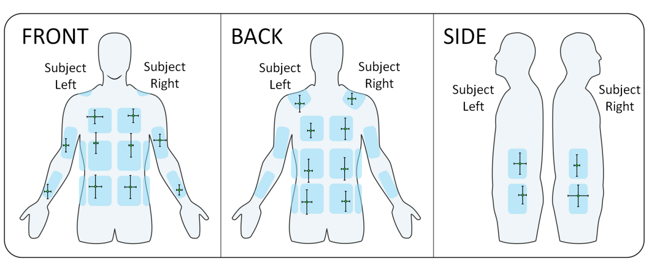


Figure 6. For each location, the centroid of x and y responses is shown along with a 1 s.d. error bar.

Free Magnitude User Study

The aim for the second psychophysical study was to determine how perceived pressure magnitude was related to inflation magnitude of the various air compartments in the Jacket.

Procedure

A form of free magnitude scaling was performed to determine users' perception of levels of compartment inflation. From an implementation perspective, it is necessary to know how a user perceives the effects in order to determine how to create them. In general, sensory transduction is a non-linear process. Free magnitudes are necessary in order to discover the intrinsic nature of the psychophysical transfer function, which tends to follow a power law [28]. The exponent of the function quantifies the extent to which the underlying physical variable is compressed (or, in some cases, expanded) in the perceptual outcome. The Likert approach, a fixed modulus, or simply establishing response extremes, all constrain the function that will emerge. To find the exponent of the power function it is necessary to allow magnitudes to vary freely. For the same reason, i.e., to avoid forcing scale use, it is not customary to pre-provide the extremes but rather to acquaint subjects with a range of representative values. In the present study, the prior localization task served this function.

On each trial, the subject was shown an image of a body with a single location marked. The corresponding compartment within the wearable was then inflated to a target level, then deflated. The subject then reported a free number (whole, fraction, or decimal) to indicate the perceived sensation magnitude, with the only constraints to use zero if no pressure was felt, and otherwise to use larger numbers for stronger sensations. Across trials, seven equally spaced levels of target force were tested, from 1.6 to 8.5 N at each location. The inflation levels corresponding to these values were set according to the outputs of FSRs that measured the amount of force exerted from the bag onto a dummy body fitted with layers of padding. To reduce the total number of trials, the 26 bag locations were subdivided into two subsets, such that the symmetric versions of each location were in different subsets. An exception was the shoulders, which were tested on both sides. The two subsets were tested in different groups of subjects. Each location was tested at each level of pressure, in random order, within a single block. This was repeated with a 5-minute break between the two successive blocks.

Results

To control for use of different scales, each participant's data was divided by his or her mean, then normalized by multiplying by the grand mean (3.0). Initial tests (between-subject comparisons on locations tested only on one side; within-subject for the shoulders) confirmed that the results for a location were symmetric across the left and right sides. Accordingly, for subsequent analyses left and right locations were combined into a single location variable, and group (as defined by which particular locations were tested on each side) was a between-subject variable.

For each location, the average response magnitude versus force was fit with a power function with a coefficient and exponent (cells with zero, 22 out of 1792 observations were excluded from the fit). The r^2 for these functions ranged across the 13 locations from .87 to .99, and averaged .95, indicating excellent power fits. Figure 7 shows the functions and Figure 8 the parameter values. The values of the exponent were under 1.0 for all locations, meaning that the perceived pressure was compressive relative to linear changes in physical pressure, i.e., an increase in pressure has a smaller perceptual effect as pressure increases. Analyses of variance on the exponents fit to individual-participant data, with factors of location and group, found only a main effect of location, $F(12, 168) = 3.20$, $p < .001$. This indicates location differences that are consistent across the subjects. A Fisher's least significant difference test using the mean square error for location divided the locations into two groups differing in degree of compression. For locations with exponents below 0.60, perceived pressure increased quite non-linearly with increases in actual pressure, showing little perceptual distinction between higher physical pressure levels. For locations with exponents above 0.60, users' distinction between increasing pressure levels was more sensitive across the range of physical values.

In contrast to the exponents of the power functions fit to the magnitude-pressure data, the coefficients were not reliably different across locations other than the shoulders. The ANOVA on group and location found an interaction between the factors, indicating inconsistent ranking by location across groups. The one apparent trend was for the shoulder location to be relatively more sensitive, as indicated by its high coefficient in both groups.

Discussion

Results from the magnitude study showed that the shoulders were the most sensitive to pressure overall. This may reflect the density of sensory receptors in this area [33], or users may simply be more attuned to pressure on the shoulders because they commonly carry loads in this area. The upper side was also sensitive to pressure relative to other areas, possibly because the inflation was opposed by the rib bones. The relative insensitivity of other areas (back forearm, mid and upper back and upper chest) should be taken into account and compensated for, if the goal is to maximize perceptual response. However, to the extent that the sensitivity differences observed here reflect the natural perceptual channel, the differential responses to pneumatic stimulation in various parts of the body will simply mimic what is felt in situations of everyday contact.

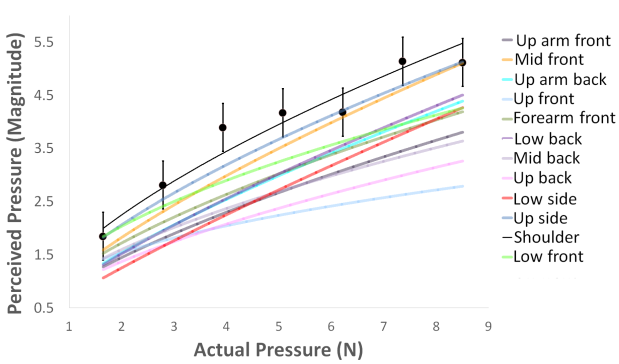
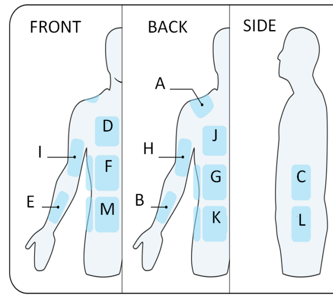


Figure 7. Power Fit lines of subjects' perceived pressure magnitude (weighted averages) versus actual pressure exerted by the air compartments. Weighted Average data points and error bars (1 s.e.m.) are shown for the shoulder location as an example of the data collected. All other locations were simplified to their power fit lines for plot clarity.



Location	Coefficient	Exponent
(A) Shoulder	1.47	0.61
(B) Forearm Back	1.43	0.51
(C) Up Side	1.33	0.63
(D) Up Front	1.16	0.41
(E) Forearm Front	1.12	0.61
(F) Mid Front	1.12	0.71
(G) Mid Back	1.08	0.57
(H) Up Arm Back	0.93	0.72
(I) Up Arm Front	0.91	0.67
(J) Up Back	0.9	0.6
(K) Low Back	0.9	0.75
(L) Low Side	0.7	0.85
(M) Low Front	0.23	0.81

Figure 8. Coefficients and Exponents of the Magnitude Power Fit Functions and corresponding locations. Highly compressive responses with exponent <0.60 highlighted in green. Exponents >0.60 highlighted in pink.

FEEL EFFECTS USER STUDY

A final study focused on the definition of an initial vocabulary of pressure and vibrotactile *feel effects* to be produced with the Force Jacket in desired applications. We extend the paradigm described in [12], where a *feel effect* (FE) is defined as a mapping between language space and haptic space. The goal of the study is to elicit canonical parameter settings in haptic space that correspond to naive users' sense memory for a given language phrase. The following subsections explain the steps required to achieve that goal: defining the haptic space, reducing and labeling the dimensions of variability, and evoking the correspondences through language.

Defining the Haptic Space

The range of possible feel effects that can be produced by the Jacket depends only on the pneumatic properties of the wearable. Irrespective of how a user experiences a feel effect, an engineer or haptics designer needs a way to specify a combination of actions in the Jacket as they unfold over time. To that end, a *Haptic Effect Editor* was developed to easily create and control haptic feedback sequences. The Haptic Effect Editor comprises two distinct GUIs, a Simple Editor and a Motion Editor, both equipped with multiple sliders to control airbag inflation parameters. Both editors operate in two effect modes: Vibration Mode (where the fluttering effect of the system is utilized to operate analogously to a vibrotactile motor) and Force Mode (where a force/pressure based stimulus is applied to the body by inflating and deflating the bag).

The *Simple Editor* allows designers to control an individual airbag's inflation and deflation sequence. The GUI provides single stroke feedback in real time as designers control various inflation parameters with sliders (see Figure 9 top). Among the parameters that can be adjusted in the *Simple Editor* are the following: *Inflation Pressure [psi]* (the speed with which the air compartment inflates); *Target Force [N]* (the target amount of force the airbag exerts on body); *Feedback Duration [ms]* (the length of time that the air compartment remains inflated); *Target Frequency [Hz]* (the speed of vibrations experienced when in Vibration Mode); *Time per Cycle [ms]* (the length of the entire feedback cycle time for periodic inflation); *Bags To Inflate* (the bags on the body where effects occur, with either single or multiple bags selected).

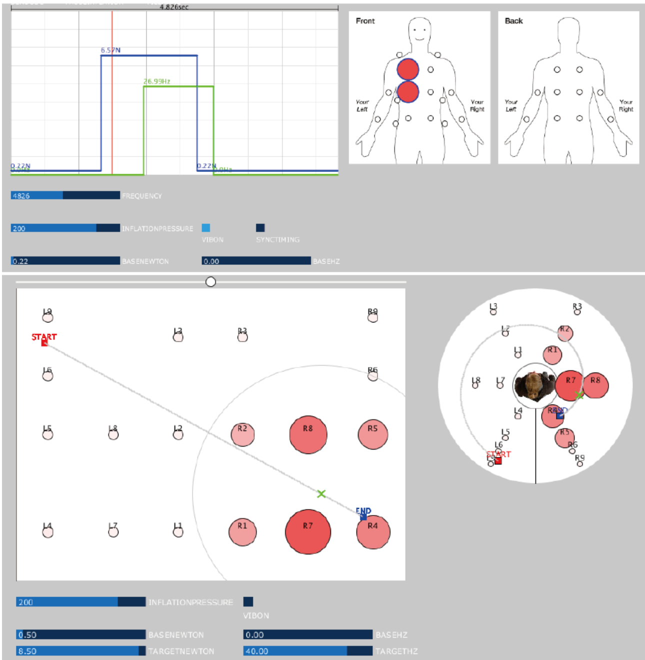


Figure 9. Haptic Effect Editor GUI (top: Simple; bottom: Motion) to be used to design custom haptic feedback with Force Jacket. Sliders for different parameters (some sliders are cropped out to save space here) and graphical visualizers of haptic effect were implemented. For motion editor, start and end points could be selected in 2D matrix.

The *Motion Editor* allows designers to create the sense of an event moving over the body. When designers select start and end points with a specific path speed, a corresponding inflation/deflation pattern will move across the body along the target line depicted in the GUI. Depending on the setting of a parameter for effect dispersion, bags will inflate around those on that target line. The target force for each airbag is inversely related to distance between bag and the target point. The maximum distance affected adjacent to the line is measured by a Spread Distance variable. The visualizer shows the successive locations of the target point and transition of target force for each bag, as depicted in the lower portion of Figure 9. In addition to the Inflation Pressure [psi] and Target Force [N], the following parameters can be adjusted in the Motion Editor: *Start and End Point [coordinates(x,y)* (the start and end locations of the bag inflation); *Motion Speed [inch/sec]* (the travel speed of the motion along its path); *Spread Distance [inch]* (the extent of the effect's dispersion from the target point, defined by which bags adjacent to the motion path are inflated).

With these editing controls it is possible to define any combination of parameter settings that the Jacket can produce. However, not all combinations will correspond to meaningful feel effects. A desired feel effect is designated by a language phrase and an initial set of parameter values. To build an initial set of FEs we ask users to fine tune a subset of the parameter values, relying on their sense memory or intuitive understanding of the experiences described. In the next section we identify the particular FEs that users were asked to tune and motivate the subset of dimensions chosen for their controls.

Reducing and Labeling the Dimensions of Variability

Fourteen feel effects (FEs) were chosen as a target vocabulary for the study, comprising examples from six families[1]: Precipitation, Enclosure, Pulse, Impact, Motion, and Motor. Within these families we chose some FEs that name extremes within the haptic-semantic dimension ("Light Rain vs. Heavy Rain", "Tap" vs. "Punch", etc.), and allow for direct comparison with prior work. The remaining FEs were chosen to explore different types of novel pneumatic haptics. As shown in Table 1, the families and their members were:

Rain: a sensation of rain created by randomly fluttering a series of airbags on subjects' shoulders simultaneously. Previous work [12] demonstrated that the semantic antonyms of "Light Rain" and "Heavy Rain" produced maximally distinct canonical parameter settings along the vibrotactile haptic dimensions corresponding to how many drops and how hard they were falling. In the current study, we investigate if the Force Jacket implementation produces the same distinction using Inflation Pressure and Target Frequency, respectively.

Pulse: a heartbeat sensation created by actuating an airbag on an area of the participant's left chest. Contrasting semantic expressions of "Racing" and "Calm Heartbeat" were chosen for this family to gain desired haptic extrema similar to those in the Rain family. Subjects could adjust heartbeat speed (realized as Time per cycle) and pounding force (Inflation Pressure).

Enclosure: three FEs actuated by airbags on multiple areas of the body to elicit the sensation of enclosure. Two types of hug were distinguished semantically using the modifiers "Adult" and "Child". Differences were predicted between participants' adjustments of how strong the hug was (realized as Target Force), how long it lasted (Duration), and how quickly the hug was initiated (Inflation Pressure). The third member of this family, "Muscle Enhancement," used multiple airbags over a broader body area to allow users to feel as though their muscles were straining against their clothing. Parameter settings manipulated both how large (Target Force) and how fast (Inflation Pressure) the muscles grew.

Strike: effects experienced by actuating one air compartment to elicit the feeling of an impact or force against the body. Semantic contrasts among "Snowball Hit," "Punch," and "Tap" are expected based on varying impact force (realized as Target Force) and impact speed (Inflation Speed).

Travel: effects experienced as a movement across different areas of the participant's body. This family included semantic phrases such as "Slime Sliding," "Snake Slithering," and "Bug Crawling" to evoke expectations of different types of locomotion, each with associated haptic stimulation. All of

[1]Following [12], a family is a set of semantically-related language phrases partially defined by at least one common haptic parameter and differentiated by others. For continuity we chose five families that overlapped with prior work and one that was distinct (Enclosure) and particularly well-suited to realization through pressure.

FAMILY	FEEL EFFECT	PARAMETERS	RANGE
PULSE	Racing Heartbeat	*Inflation Pressure (psi)*	18 – 48
	Calm Heartbeat	*Time per Cycle (ms)*	500 – 2500
ENCLOSURE	Child Hug	*Duration (ms)*	2000 – 10000
	Adult Hug	*Target Force (N)*	1.5 – 8.5
	Muscle Enhancement	*Inflation Pressure (psi)*	18 – 48
RAIN	Light Rain	*Target Frequency (Hz)*	4 – 35
	Heavy Rain	*Inflation Pressure (psi)*	18 – 48
STRIKE	Snowball Hit on Chest	*Target Force (N)*	1.5 – 8.5
	Fist Punch on Side	*Inflation Pressure (psi)*	18 – 48
	Hand Tap on Shoulder		
TRAVEL	Slime Dripping on Back	*Target Force (N)*	1.5 – 8.5
	Snake Slithering around Body	*Motion Speed (in/s)*	5.6 – 33.8
	Bug Crawling up Arm	*Impact Dispersion (in)*	5.6 - 16.9
MOTOR	Motorcycle Vibration	*Target Force (N)* *Target Frequency (Hz)*	1.5 – 5 4 – 35

Table 1. Feel Effect Families grouped based on shared refinement parameters. Gray denotes vibrotactile effects.

these effects have a Motion Speed parameter in common, allowing subjects to control the creatures' velocity against their bodies. Each FE also has one or more parameters labeled with an animal-specific description (e.g., how strongly the snake constricts (realized through Target Force), how quickly the bug moves its legs (Target Frequency), or how heavy and spreadable the slime is (Target Force and Impact Dispersion, respectively).

Motor: vibrotactile feedback created by rapidly actuating all airbags against the participant's body to mimic the vibration experienced in a running vehicle. "Motorcycle," the sole semantic term used in this family, is a specific type of vehicle that can be characterized by the force and frequency of vibration experienced.

Eliciting Canonical Parameter Settings through Language

Participants (N = 17, 8 female, 9 male), aged 18-60 (M = 26.31, SD = 2.16) were recruited for the feel effect studies and compensated with 15 dollars. These studies each lasted 40-60 minutes.

Procedure

Similar to the procedure for the basic perception studies, users were asked to wear the Force Jacket and stand (or sit if preferred) 36 inches away from a computer monitor. Facing the monitor, they used their right hand to control a mouse for responses. Experimenters monitored and controlled the pneumatic system behind the subjects as shown in Figure 1C.

Participants were shown a language phrase such as, "I feel muscles growing on my upper body" as well as two or three labelled parameter scales (see Figure 10) and asked to experiment with different combinations of parameters, in order to find the settings that gave the most realistic expression of the language description. Each scale contained five possible levels, increasing in value from left to right. As in [12], parameter values were initially set to reflect a plausible range for the effect, rather than for the full range of the device, in order to promote task completion with few adjustments. When beginning a new effect, the participant experienced a preview as produced by parameter settings at a baseline level in the middle of the scale. After setting parameters, participants experienced the resulting effect and provided a goodness rating on a scale of unacceptable (not realistic) to perfect (the most realistic). If participants did not experience any sensation, they were asked to rate the effect as "No feeling". Participants set parameters five times for each of the fourteen target effects, given in random order.

Following the study, participants were asked to complete a survey that requested their opinions of the experienced FEs as well as additional effects that they would enjoy trying.

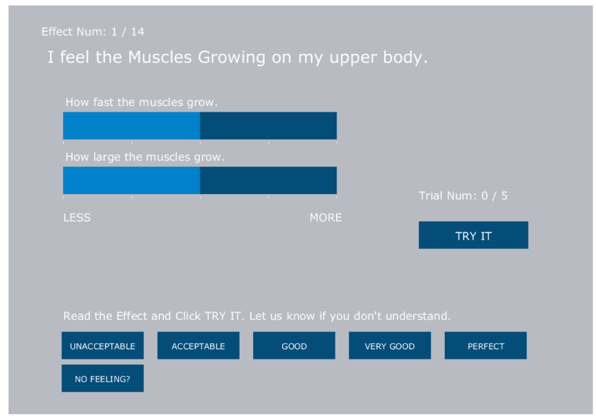


Figure 10. GUI used in the feel effect user study.

Results

For each of the 14 FEs, participants provided six goodness ratings (including baseline). Parameter settings from the participant's most positive ratings were considered to represent each effect. A histogram of the distribution of these settings across participants, for each parameter of each effect, is shown in Table 2.

In the post-study surveys, participants were asked to choose which of the fourteen feel effects they liked and disliked. Table 3 shows the number of likes and dislikes for each haptic effect based on participants' responses.

Discussion

It was known from previous work on feel effects that vibrotactile inputs alone are inherently ambiguous; however, people can agree on an optimal range of input values for an intended purpose if they are given a semantic context. The question in the current work was whether similar disambiguation with a grounding phrase would occur for pressure input. Since sustained pressure relies on different haptic receptors, is more diffuse, is realized in a different form factor, etc., it is quite possible that what was demonstrated in the vibrotactile case, in terms of an underlying semantics of touch, would fail to transfer. Results from this study support the idea that properties of semantic-haptic space can also be captured by feel effects that rely on pressure haptics, with some limitations. From Table 3, it is clear that we were able to create effects that were given high goodness ratings (motorcycle, heartbeat, snake, child hug). For these effects, the results in Table 2

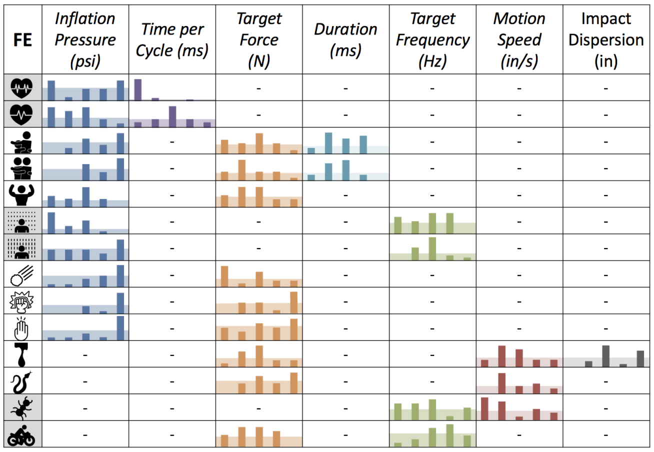


Table 2. Histograms of choices for varied parameters of each feel effect. The x axis of each box represents increasing values of the parameter. (see Table 1). The y axis varies but all distributions sum to 17. The order of feel effect on left column takes same order as Table 1. A gray field indicates that the vibration mode was used.

indicate optimal parameters under the current hardware. As in [12], parameter settings followed semantic expectations; both that study and the current one, for example, show a decrease in stimulation intensity from heavy to light rain. However, it is also clear that some effects (punch, tap, snowball) failed to render their semantic goals. For these effects, Table 2 points to limitations in what can be achieved with the current implementation. Next, some salient points regarding specific effects are reviewed.

Participants reported greatest liking for the "Motorcycle Vibration" and "Snake Crawling" effects. Both of these effects also fell within the top five highest goodness ratings, with the "Motorcycle Vibration" effect being rated most realistically created. The "Heartbeat" effects were also very well liked; however, the rated realism of the calm heartbeat was high and the racing heartbeat was low. Parameter settings indicate that participants were relatively indifferent to the force exerted by the heartbeat, but the speed of the racing heartbeat was an important consideration. For the ”Calm Heartbeat" effect an intermediate cycle time was desired, while participants consistently choose the fastest cycle time for ”Racing Heartbeat," suggesting that they desired a much faster effect.

"Punch", "Hand Tap" and "Snow Ball hit" were among effects rated lowest in goodness, and also liked least. In contrast to the effect that were liked and found realistic, these effects consisted of a single air compartment inflation. Participants consistently chose the highest inflation pressure levels for these three effects, suggesting that maximum impact speed is desired. The Force Jacket is not yet necessarily suitable for quick impacts without further adjustments to the system such as a stronger air compressor and control algorithm. Participants were apparently able to distinguish between the force profiles that would be associated with these effects. A stronger impact force level was chosen for "Snowball" and "Punch," while the lowest was desired for "Tap," which is consistent with physical definitions of these effects. Future work will address the question raised in the Feel Effect paper by Israr et al.[12], as to whether the optimized effect parameters correspond well to the descriptive language phrase.

FEEL EFFECT	LIKE	DIS-LIKE	GOODNESS RATING
Motorcycle Vibration	14	2	4.39
Muscle Enhancement	8	4	4.18
Calm Heartbeat	9	2	4.12
Adult Hug	6	5	3.76
Snake Slithering around Body	12	1	3.71
Bug Crawling Up Arm	9	4	3.47
Snowball Hit on Chest	3	11	3.29
Fist Punch on Side	1	13	3.12
Heavy Rain	6	6	2.94
Slime Dripping on Back	6	5	2.94
Light Rain	7	7	2.65
Child Hug	9	2	2.65
Hand Tap on Shoulder	1	11	2.47
Racing Heartbeat	10	3	1.29

Table 3. Feel effects ordered based on goodness rating out of 5, where 5 is perfect and 1 is unacceptable. Results of post user study survey regarding likes / dislikes are shown as a gradient from most liked (green) to most disliked (red).

APPLICATIONS

The primary motivation of this research was to enhance the entertainment value of HMD-based visual VR experiences in games and movies, by providing on-body force feedback. Full 360 degree VR is a fitting counterpart to the Force Jacket's capability to provide feedback all around the body. For this reason, three different prototype, VR applications were created (Figure 11).

In the snowball flight application, people participated in a snowball fight with a virtual character where they could throw snowballs and receive the impact of a snowball via a haptic cues (Figure 11A). In the second prototype VR application, people experienced a snake crawling around their bodies. As they saw the snake moving around them, not only could they see it, but they experienced it squeezing their torso and chest as it moved along its path (Figure 11B). In the third protoype VR application, the Kinect and Vive controller was used to dynamically change the haptic feedback according to users' actions and explore the effects of changing the perceived muscularity of the body.

As described earlier, the muscle enhancement effect can give the impression of greater muscularity (Figure 11C). Although previous research has demonstrated a similar idea of altering users' body cognition with vibrotactile haptic effects [16] or visual-feedback alternation [20], the Force Jacket is unique in the way the system can selectively control different body parts (e.g. arms, abs or chest) to undergo "body building" or the visual and haptic stimuli that create bulky muscles. In the prototype VR application created, people stood in a virtual bathroom and watched (and felt) themselves transform into a muscular hero. This could provide a powerful experience for

Figure 11. Prototype VR Applications of the Force Jacket - A: Interactive snowball fight; B: Friendly snake crawling on user; C: Transformation into a muscular hero.

gaming applications, where a playable character could become more muscular over the course of training. Heartbeat effects could also be used to control users' sense of tension or anxiety, fatigue, etc.

Beyond our prototype applications, the jacket also has a strong potential for remote communication applications, like a hug delivered from afar. While an early pneumatic haptic interface study proposed similar applications [30, 29], the feel effect study in this paper suggests which parameters are relevant to various effect types and their optimal settings. Further non-VR applications such as training, where trainees directly sense the physical consequences of their actions, are possible. Similarly, the haptic force stimulus from the Jacket could assist rehabilitation for patients who require variable pressure feedback to sense body position.

LIMITATIONS AND FUTURE WORK

We believe that this haptic technology and its psychophysical evaluation should initiate a process of development and application. At the same time, clear limitations point to directions for research and development. With the system consisting of 26 individually controlled solenoid valves that are actuated by a large air compressor and vacuum, the overall system set-up is very bulky and confining for the user. Also, with the surround body effects that the wearable can achieve, a 360 degree virtual reality experience is possible; however, the user's ability to rotate or move in the VR space is limited by the tubing that tethers them to the air and vacuum supply. In the future, compressed air canisters and large open diameter outlets in each bag could replace the air compressor and vacuum respectively to allow for an untethered experience, although this approach has other limitations in return: the maximum available force and speed of the haptic feedback. Previous research on 3D printing technique for inflatables and internal tubing [32, 27] could be applied to reduce the complex tubing and increase the resolution of airbags.

Other technical limitations include the use of FSR, as their sensor readings can be minimally affected by body motion. While this was not a critical issue for the current study, where users were passively feeling the effect, it needs to be addressed in the future for a practical full-body immersive experience. This could be compensated for, to some extent, with a body motion tracking system and filtering algorithm. Additionally, it should be noted that the system is not greatly affected by the inflation of one or more bags. The system was designed to operate as a compilation of 26 individually controlled inflatable bags that operate both independently and in sync. Noise of the compressor and vacuum pump is another issue for practical usage that was minimized by isolating them in a different room. Additionally, since all of the airbags were connected to the same manifold, bags could not experience individual inflation speeds. If multiple effects with different inflation speeds were to be provided, the implementation would require a complex design, either with valves that can adjust inflation speed, or multiple valves, each connected to a dedicated air pressure pump. Also, airbag control with precise pressure feedback could be implemented using advanced algorithms [6] as well as a variable-pressure vacuum.

Work will be continued to enhance current VR demos as well as create new immersive AR and VR experiences that incorporate combinations of all of the effects that were tested during the feel effect study. While all user studies conducted in this paper were with haptic feedback only, evaluating the combination with visual effects from HMD is another interesting research direction for the multi-modal sensation research domain. Additional effects and sensations will be explored further as well. A Force Jacket effect prototyping workshop could be an interesting approach to expanding the Jacket's library of effects by letting designers and researchers create their own effects with the *Haptic Effect Editor* software.

CONCLUSION

This paper introduces Force Jacket, a novel wearable haptic interface that can provide strong and variable forces to the upper body along with vibrotactile sensations, using pneumatically actuated airbags. This system offers the unique capability of delivering haptic actuation over large areas with a relatively low number of actuators, as compared to conventional techniques. Furthermore, the use of inflatable airbags offers the ability to apply strong static pressure to the user as well as high frequency vibrations, which is not possible with other techniques. To validate the efficacy of this approach a series of user studies have been conducted to evaluate basic human perception of this type of haptic actuation in terms of location and magnitude on the user's body. These findings were incorporated into a haptic effects editor that allows designers and engineers to create custom higher order haptic effects, and a second users study was conducted to create a library of haptic sensations. Finally, this library of effects was used to enhance three virtual reality experiences. Ultimately the Force Jacket provides a new haptic actuation method that can deliver far more immersive experiences by engaging the whole body.

ACKNOWLEDGMENTS

We thank Ali Israr for initial concept design, Moshe Mahler, Kyna McIntosh, James Krahe, Michelle Ma, Sammie Ma and James Kennedy for artistic support, Maarten Bos for user study support and Joohyung Kim, Daniel Campos Zamora and Sebastian Sanchez for airbag sealing. We also appreciate all user study participants.

REFERENCES

1. Ahmed Al Maimani and Anne Roudaut. 2017. Frozen Suit: Designing a Changeable Stiffness Suit and its Application to Haptic Games. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, 2440–2448.
2. Faisal Arafsha, Kazi Masudul Alam, and Abdulmotaleb El Saddik. 2012. EmoJacket: Consumer centric wearable affective jacket to enhance emotional immersion. In *Innovations in Information Technology (IIT), 2012 International Conference on*. IEEE, 350–355.
3. Hrvoje Benko, Christian Holz, Mike Sinclair, and Eyal Ofek. 2016. Normaltouch and texturetouch: High-fidelity 3d haptic shape rendering on handheld virtual reality controllers. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. ACM, 717–728.
4. Mourad Bouzit, Grigore Burdea, George Popescu, and Rares Boian. 2002. The Rutgers Master II-new design force-feedback glove. *IEEE/ASME Transactions on mechatronics* 7, 2 (2002), 256–263.
5. TN Games. PHANTOMSENSE. `http://tngames.com/`. http://tngames.com/, Accessed: 2017-09-19.
6. Morgan T Gillespie, Charles M Best, and Marc D Killpack. 2016. Simultaneous position and stiffness control for an inflatable soft robot. In *Robotics and Automation (ICRA), 2016 IEEE International Conference on*. IEEE, 1095–1101.
7. Kristian Gohlke, Eva Hornecker, and Wolfgang Sattler. 2016. Pneumatibles: Exploring Soft Robotic Actuators for the Design of User Interfaces with Pneumotactile Feedback. In *Proceedings of the TEI'16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*. ACM, 308–315.
8. Steve Guest, Jean Marc Dessirier, Anahit Mehrabyan, Francis McGlone, Greg Essick, George Gescheider, Anne Fontana, Rui Xiong, Rochelle Ackerley, and Kevin Blot. 2011. The development and validation of sensory and emotional scales of touch perception. *Attention, Perception, & Psychophysics* 73, 2 (2011), 531–550.
9. H2L. Unlimited Hand. `http://unlimitedhand.com/en/`. http://unlimitedhand.com/en/, Accessed: 2017-09-19.
10. Liang He, Cheng Xu, Ding Xu, and Ryan Brill. 2015. PneuHaptic: delivering haptic cues with a pneumatic armband. In *Proceedings of the 2015 ACM International Symposium on Wearable Computers*. ACM, 47–48.
11. Ali Israr and Ivan Poupyrev. 2011. Tactile brush: drawing on skin with a tactile grid display. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 2019–2028.
12. Ali Israr, Siyan Zhao, Kaitlyn Schwalje, Roberta Klatzky, and Jill Lehman. 2014. Feel effects: enriching storytelling with haptic feedback. *ACM Transactions on Applied Perception (TAP)* 11, 3 (2014), 11.
13. Yukari Konishi, Nobuhisa Hanamitsu, Kouta Minamizawa, Ayahiko Sato, and Tetsuya Mizuguchi. 2016. Synesthesia suit: the full body immersive experience. In *ACM SIGGRAPH 2016 VR Village*. ACM, 20.
14. Takayuki Kosaka, Hajime Misumi, Takuya Iwamoto, Robert Songer, and Junichi Akita. 2011. " Mommy Tummy" a pregnancy experience system simulating fetal movement.. In *SIGGRAPH Emerging Technologies*. 10.
15. Emilia Koskinen, Topi Kaaresoja, and Pauli Laitinen. 2008. Feel-good touch: finding the most pleasant tactile feedback for a mobile touch screen button. In *Proceedings of the 10th international conference on Multimodal interfaces*. ACM, 297–304.
16. Yosuke Kurihara, Taku Hachisu, Katherine J Kuchenbecker, and Hiroyuki Kajimoto. 2013. Jointonation: robotization of the human body by vibrotactile feedback. In *SIGGRAPH Asia 2013 Emerging Technologies*. ACM, 11.
17. Pedro Lopes, Sijing You, Lung-Pan Cheng, Sebastian Marwecki, and Patrick Baudisch. 2017. Providing Haptics to Walls & Heavy Objects in Virtual Reality by Means of Electrical Muscle Stimulation. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, 1471–1482.
18. Karon E MacLean. 2008. Foundations of transparency in tactile information design. *IEEE Transactions on Haptics* 1, 2 (2008), 84–95.
19. Thomas H Massie, J Kenneth Salisbury, and others. 1994. The phantom haptic interface: A device for probing virtual objects. In *Proceedings of the ASME winter annual meeting, symposium on haptic interfaces for virtual environment and teleoperator systems*, Vol. 55. Chicago, IL, 295–300.
20. Jun Nishida, Hikaru Takatori, Kosuke Sato, and Kenji Suzuki. 2015. CHILDHOOD: wearable suit for augmented child experience. In *Proceedings of the 2015 Virtual Reality International Conference*. ACM, 22.
21. Jifei Ou, Mélina Skouras, Nikolaos Vlavianos, Felix Heibeck, Chin-Yi Cheng, Jannik Peters, and Hiroshi Ishii. 2016. aeroMorph-Heat-sealing Inflatable Shape-change Materials for Interaction Design. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. ACM, 121–132.
22. Conor OâĂŹSullivan and Angela Chang. 2006. An activity classification for vibrotactile phenomena. *Haptic and Audio Interaction Design* (2006), 145–156.

23. Frank G Palmer, Zhigang Zhu, and Tony Ro. 2012. Wearable range-vibrotactile field: design and evaluation. In *International Conference on Computers for Handicapped Persons*. Springer, 125–132.

24. Henning Pohl, Peter Brandes, Hung Ngo Quang, and Michael Rohs. 2017a. Squeezeback: Pneumatic Compression for Notifications. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, 5318–5330.

25. Henning Pohl, Franziska Hoheisel, and Michael Rohs. 2017b. Inhibiting Freedom of Movement with Compression Feedback. In *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. ACM, 1962–1969.

26. Luigi Russolo. 1986. The Art of Noises. Translated by Barclay Brown. *New York: Pendragon* (1986).

27. Valkyrie Savage, Ryan Schmidt, Tovi Grossman, George Fitzmaurice, and Björn Hartmann. 2014. A series of tubes: adding interactivity to 3D prints using internal pipes. In *Proceedings of the 27th annual ACM symposium on User interface software and technology*. ACM, 3–12.

28. Stanley S Stevens. 1957. On the psychophysical law. *Psychological review* 64, 3 (1957), 153.

29. Nobuhiro Takahashi, Ryuta Okazaki, Hiroyuki Okabe, Hiromi Yoshikawa, Kanako Aou, Shumpei Yamakawa, Maki Yokoyama, and Hiroyuki Kajimoto. 2011. Sense-roid: Emotional haptic communication with yourself. In *Proceedings of Virtual Reality International Conference (VRIC 2011)*.

30. James Keng Soon Teh, Adrian David Cheok, Roshan L Peiris, Yongsoon Choi, Vuong Thuong, and Sha Lai. 2008. Huggy Pajama: a mobile parent and child hugging communication system. In *Proceedings of the 7th international conference on Interaction design and children*. ACM, 250–257.

31. Jan BF van Erp and Michiel MA Spapé. 2003. Distilling the underlying dimensions of tactile melodies. In *Proceedings of Eurohaptics*, Vol. 2003. 111–120.

32. Marynel Vázquez, Eric Brockmeyer, Ruta Desai, Chris Harrison, and Scott E Hudson. 2015. 3D Printing Pneumatic Device Controls with Variable Activation Force Capabilities. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. ACM, 1295–1304.

33. Sidney Weinstein. 1968. Intensive and extensive aspects of tactile sensitivity as a function of body part, sex and laterality. In *the First Int'l symp. on the Skin Senses, 1968*.

34. Lining Yao, Ryuma Niiyama, Jifei Ou, Sean Follmer, Clark Della Silva, and Hiroshi Ishii. 2013. PneUI: pneumatically actuated soft composite materials for shape changing interfaces. In *Proceedings of the 26th annual ACM symposium on User interface software and Technology*. ACM, 13–22.

35. Steve Yohanan and Karon E MacLean. 2009. A tool to study affective touch. In *CHI'09 Extended Abstracts on Human Factors in Computing Systems*. ACM, 4153–4158.

36. Yongjae Yoo, Taekbeom Yoo, Jihyun Kong, and Seungmoon Choi. 2015. Emotional responses of tactile icons: Effects of amplitude, frequency, duration, and envelope. In *World Haptics Conference (WHC), 2015 IEEE*. IEEE, 235–240.