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Tactile displays: Overview and recent advances

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Abstract

Tactation is the sensation perceived by the sense of touch, and is based on the skin's receptors. Touch is a common medium used by the general population and the sensory impaired. Tactile substitution can be used by the blind or deaf in order to: (a) enhance access to computer graphical user interfaces and (b) enhance mobility in controlled environments.

The skin nerves can be stimulated through six types of receptors by mechanical, electrical, or thermal stimuli. Modalities, such as vibration and pressure, can stimulate these receptors. Advances in tactile communication using implementations of the actuating devices have been developed via several new technologies. These technologies include static or vibrating pins, focused ultrasound, electrical stimulation, surface acoustic waves, and other.

This paper is a review of the state-of-the-art in the physiological and technological principles, considerations and characteristics, as well as latest implementations of microactuator-based tactile graphic displays. We also review fabrication technologies, in order to demonstrate the potential and limitations in tactile applications.

Keywords: Tactile displays; Tactile communication; Tactation; Tangible interface; MEMS

1. Introduction

A tactile display is a human–computer interface that can reproduce as closely as possible the tactile parameters of an object, such as shape, surface texture, roughness and temperature. Tactile displays have been proposed as an interface in *Virtual Environment* (*VE*)–*Virtual Reality* (*VR*) applications [1,2], as feedback in teleoperation, as a complement or substitution of the visual presentation of information, and as tactile communication in mobile environments [3].

This paper aims to review all relevant achievements in the field and to summarize the various specifications that may help researchers and engineers in future tactile-interface developments.

Tactile sensations are perceived via mechanoreceptive units embedded in the outer layers of the skin, which when activated transmit signals to the brain. By stimulating the human skin to induce tactile perception, tactile displays provide an important alternative of information transmission through the tactile channel for people with vision or hearing impairments [4,5]. Such tactile stimulation can be accomplished in various technologic ways. Solutions based on mechanical needles actuated by electromagnetic technologies (solenoids, voice coils), piezoelectric crystals, shape memory alloys, pneumatic systems, and heat pump systems based on Peltier modules have been proposed. Other methods, such as using electrorheological fluids (ERF) and magnetorheological fluids (MRF), which change viscosity and therefore rigidity under the application of an electric or magnetic field, respectively, are still under investigation. On the other hand, technologies dedicated to medical applications, such as electrotactile and neuromuscular stimulators, have not yet been used because of their invasive nature. The methodology used in VE systems was inspired from matrix pin-printer technologies and Braille systems for the blind. In order to present refreshable two-dimensional tactile patterns, a tactile display with a

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large number of identical but individually addressable tactile stimulators is desirable, especially when used for sensory substitution for the visually impaired community. Among various tactile displays that are pneumatically, magnetically, thermally, or piezoelectrically driven [2,6–8], electrotactile displays have the advantages of simple structures, low power consumption, and low cost when the number of stimulators increases [1]. Furthermore, micromachining may be employed to fabricate high-density electrotactile stimulator arrays with the potential of further cost reduction and miniaturization.

This paper presents an up-to-date review of the state-of-the-art in tactile display technologies, as well as current research on the physiologic characteristics of the skin. The first section examines the human tactual sensory system in order to provide an understanding of how we, as humans, interface with the world around us. The second section presents a classification of the implementations that attempt to automatically convert the images from visual/audio to tactile. Specific techniques used in these systems are detailed along with their existing and potential applications.

2. Skin physiology

The skin is the body's largest organ and acts as a sensory port of external stimuli having several kinds of sensors. These properties of the skin are exploited in tactile interfaces. The skin's complexity greatly affects the design and performance of tactile displays, so in order to design better interfaces, it is imperative that we have a deep understanding of the several modalities of the skin's sensors and nerves and their response to external stimuli. Following we make a thorough presentation of the skin's anatomy and its spatiotemporal tactile perceptive characteristics and biomechanical properties.

2.1. Skin anatomy

On the surface of the skin there is a conglomeration of dead cells. Underneath the surface, there are very thin and distinct layers, the *Epidermis*, the *Dermis*, and the *Hypodermis*. The Epidermis, which has a thickness that varies from 0.4 to 1.6 mm, is an important layer as it houses the langerhans cells responsible for the immunology of the skin and the melanocytes and tyrosinase enzyme, responsible for the production of melanin and color. The second layer, or Dermis, which is five to seven times thicker than the Epidermis, lies below the Epidermis and is connected to it by the basement membrane. The Dermis consists of a thick connective membrane criss-crossed by blood vessels, lymphatic vessels, nerve fibers, and many sensory nerve endings. Collagen and elastin protein fibers, the two main components of the Dermis, act as a structural support system for the nerve fibers, hair follicles, blood vessels, and oil and sweat glands also located in this layer, and provide the skin with strength and elasticity. The Hypodermis, the skin's third and last layer, binds the skin with the muscle tissues. This layer is highly elastic and has fat cells acting as "shock absorbers", thereby supporting delicate structures, such as blood vessels and nerves.

2.2. Receptors and modalities of the skin

2.2.1. Receptors

The characteristics of the skin vary along the many parts of the human body. However, the major part of the current research work is related to the glabrous skin (without hair), as most of the applications developed so far are used either on the palm and finger or some other parts of the body, such as the abdomen or the arms. The skin is sensitive to pressure (positive or negative), vibration, temperature, electric voltage, and current.

In order to facilitate the sense of touch, the skin includes seven classes of mechanoreceptors, two classes of thermoreceptors, four classes of nocioceptors, and three classes of proprioceptors [7]. Table 1 outlines seven mechanoreceptors and their respective sensory modalities. An analysis of each modality reveals different levels of appropriateness for the construction of a tactile display. Four kinds of mechanoreceptors lay on the skin tissue [4–6,9], each at a specific depth in the skin. On the palm, the shallowest (Meissner corpuscle) and the deepest (Pacini corpuscle) mechanoreceptor are located below the surface by about 0.7 and 2 mm, respectively. Among the different classes of mechanoreceptors, the most commonly exploited in tactile display applications are the Merkel cells for pressure sensation, the Meisner corpuscle for low-frequency vibration, and the deep Pacinian corpuscle for high-frequency vibration [10]. Merkel cells and Meisner corpuscles are located

Table 1
Human mechanoreceptors and their corresponding sensory modalities

Receptor	Class	Sense modality	Frequency range (most sensitive at)	Receptors (cm^2) at fingertip
Meissner corpuscle	RAI	Stroking, fluttering	10–200 Hz (200–300 Hz)	140
Merkel disk receptor	SAI	Pressure, texture	0.4–100 Hz (7 Hz)	70
Pacinian corpuscle	RAII	Vibration	40–800 Hz (200–300 Hz)	21
Ruffini ending	SAII	Skin stretch	7 Hz	9
Hair follicle	RA	Stroking, fluttering	?	–
Hair	–	Light stroking	?	–
Field	–	Skin stretch	?	–

at 0.7–0.9 mm below the surface of the skin, while Pacinian corpuscles are found at 2 mm.

Heat and temperature are also important modalities for the sense of touch. Although it seems that the skin is sensitive to temperature, our receptors cannot measure the exact temperature of the surface, but rather, they feel the thermal energy flow and as a result, temperature difference is used to add quality characteristics to the tactual sense. Also, it is known that the actual skin temperature can significantly influence the sense of tactation. Experiments have shown that it is possible to discriminate between two contact points based on the thermal flux on fingers [11–13].

The parameters that primarily affect the design of a tactile display for each receptor are:

- spatial resolution and sensitivity of the sensors,
- temporal processing characteristics (adaptation, summation). These characteristics classify mechanoreceptive units into four categories: rapidly adapting I and II (RAI and RAII) and slowly adapting I and II (SAI and SAII), whose end organs are Meissner corpuscles, Pacinian corpuscles, Merkel cell neurite complexes, and Ruffini endings, respectively [14],
- spatial features of processing,
- delays in processing information (0.4–120 m/s).

As shown in Table 2 the information capacity of the skin is lower than other human sensors but the skin is faster than the eye.

Table 2
Comparison of the body's main sensors

	Information capacity (bits/s)	Temporal acuity (ms)
Fingertip	10^2	5
Ear	10^4	0.01
Eye	10^6–10^9	25

2.2.2. Modalities

2.2.2.1. Vibration. The Pacinian corpuscles are the mechanoreceptors responsible for detection of higher frequency vibrational stimuli. Pacinian corpuscles lay deep in the dermis and are the largest touch receptors. They are the fastest adapting of the class of fast-acting receptors, as they respond quickly to changing stimuli. The perceived intensity of vibration varies as a function of frequency as well as amplitude. Their optimal sensitivity is around 250 Hz, and drops rapidly at frequencies below 50 Hz or above 600 Hz [7].

2.2.2.2. Pressure and stroking. Although vibration is merely the time variance of pressure around an equilibrium level, it remains a distinct dermal sensory channel from both pressure and stroking. Both pressure and stroking communication channels require the accurate generation of static or low-time variant-pressure distribution across the skin surface [7].

2.2.2.3. Skin stretch. Displays using the perception of stretch on the skin have been demonstrated. These devices require at least two points of firm contact with the skin, which are drawn apart to stretch the skin. Any material between the skin and the stimulator may cause the contact points to slip. As a result, stretch makes a poor mobile or garment-integrated communications channel and it is avoided in such applications [7,15].

2.2.2.4. Texture, stroking, and fluttering. The sensations of texture, light stroking, and fluttering are subtle sensations that are only perceptible directly on the skin surface [7].

2.2.3. Skin sensitivity

Various parts of the body were used in several applications, such as the torso. Most of the tactile applications though, use the palm and finger tip which, apart from the lips, is the most sensitive to touch than any other part of the human body [16,2,17].

Several researchers have studied the spatial resolution and sensitivity of the human skin [18–22]. Their findings show that the minimum distance between two vibrating signals that are correctly discriminated lays between 0.8 and 1.2 mm, depending on the signal frequency. Low-frequency signals 1–3 Hz and 18–56 Hz excite the denser SAI and RAI receptors and achieve a high resolution, while high-frequency signals above 250 Hz excite the sparse RAII and present a lower resolution. On the other hand, RAII are more sensitive than SAI and have lower thresholds.

The skin can be regarded as a spatial low-pass filter for the surface stress distribution [9]. If we assume the human skin to be a uniform, homogeneous elastic body, we can calculate the attenuated pressure $P_z(k)$, at depth z in the skin, of a pressure signal $P(k)$ with wave number vector $k = (k_x, k_y)$ by:

$$P_z(k) = P(k)\mathrm{e}^{-|k|z} \tag{1}$$

Eq. (1) suggests that:

(1) Different mechanoreceptors (located at various depths) receive a different part of the spectrum of the surface-stress signal [23].
(2) Fine patterns with wavelength smaller than 1 mm hardly reach any receptor because of the exponential attenuation, except in the parts with very thin skin [24].

A mechanistic model of skin was developed by Phillips et al. [25] to predict the state of stress and strain at mechanoreceptor terminals within the skin when any static stimulus having a defined spatial profile (e.g., a grating) is applied to the surface. The model was based on standard continuum mechanics theory. It was assumed that: (i) for small deformations, the mechanical properties of skin are adequately approximated by those of a homogeneous, elastic, isotropic medium, and (ii) the effect of a complex stimulus can be determined by decomposing it into simple subunits and then superimposing their effects. The previous aforementioned study showed that: (i) the principle of superposition may be considered to apply when the stimuli are defined by applied force but not displacement, (ii) the static mechanical properties of skin may be adequately approximated by those of an ideal medium, at least for surface deflections of the order of 1 mm or less, and (iii) the local stimulus determining the SA response is the maximum compressive strain at the terminal.

3. Device implementation

Exploiting the modalities of the skin's sensors, the systems implemented so far can be classified into the following major categories based on:

– static pressure or vibration (mechanical energy),
– electric field,
– thermal flow (temperature difference).

Furthermore, the mechanical or electrical stimulation of the receptors classifies the devices into three categories. Pressure (exerted by pin devices), vibration, wave, and ERF-based devices stimulate the mechanoreceptors using mechanical energy and exploit the modality of each mechanoreceptor. On the other hand, a second class of devices that directly activate nerves using electric field has been proposed. A third class uses focused ultrasound in order to activate receptors directly or through ultrasound radiation pressure. The previous modalities are mainly used to present spatial information, whereas thermal flow is used to add quality characteristics in the data presented, simulating color in vision. Some applications combine different modalities by selectively activating different receptors and creating a richer communication.

3.1. Mechanical energy devices

In order to overcome the difficulties presented by the Braille paper usage, the earlier designs were using reconfigurable pressure tactile displays. In pin-based tactile displays, the tactile pattern is formed by an array of pins that can either be in one of two positions (up or down) or vibrate in the vertical direction so that both the pressure and vibration modalities of the skin are engaged. The array of pins can be used as a graphic display or a Braille display.

The pins are moved by actuators based on piezoelectricity [26–29], electrically-controlled pneumatic valves [30], or electromagnetic forces [4,9]. Currently, piezoelectric Braille displays dominate the market although they are quite expensive. They all use the same technology, a small piece of ceramic substrate that is shaped to the right dimensions.

3.1.1. Vibration-based devices

In the past 15 years, a significant amount of research has been performed on vibration-based (*Vibrotactile*) interfaces [7,15,16,31–45].

In 2000, Hayward et al. described a tactile-display device, which was relying on lateral skin-stretch stimulation [15]. It was constructed from an array of 64 closely-packed piezoelectric actuators connected to a membrane. The deformations of this membrane caused an array of 112 skin contactors to create programmable lateral-stress fields in the skin of the finger pad. Using similar rationality, Pasquero et al. constructed a tactile display system (STReSS) that produced "tactile movies" by using rapid sequences of tactile images refreshed at a rate of 700 Hz [40]. The display used an array of 100 laterally-moving skin contactors designed to create a time-varying programmable strain field at the skin surface. The density of the array was of one contactor per square millimetre, resulting in a device with high spatial and temporal resolution.

Ikei et al. presented the design of a haptic texture display consisting of fifty vibratory pins that evoke a virtual touch sensation of textured surfaces contacted to the user's fingerpad [34,35]. A pin-drive mechanism was fabricated by adjusting the natural frequency to expand the displacement of a piezoelectric actuator and was controlled by a system that enabled amplitude changes in 200 steps. Sensation intensity was scaled and indicated by a power function of pin amplitude. The pins used vibrated at a frequency of 250 Hz, corresponding to the stimulation for Pacinian corpuscle.

ComTouch® is a device that augments remote-voice communication with touch by converting hand pressure into vibrational intensity in real time and, therefore, enriching interpersonal communication by complementing voice with a tactile channel [38].

Toney et al. integrated a vibrotactile display in a shoulder pad, advancing the use of vibrotactile displays in wearable devices [7]. Vibration is a suitable candidate for clothing-insert-based tactile displays as the scale of the impulse and geometry of a vibration device facilitate easy integration into small garment spaces. Furthermore, Tsukada et al. proposed a wearable interface called "Active-Belt" that enabled users to obtain multiple directional information with vibratory-activated tactile sense [44]. Using Nitinol®, a shape memory alloy (SMA), a small and flexible tactile display was built for the torso by Nakamura et al. [16]. The design generated large stresses and strains and was able to fit in the thin space of a vest. In experimental tests conducted on the SMA, a pulse 1 A in amplitude and 1 s in duration produced an average displacement of 3.7 mm and peak pressures about 20 times the touch threshold for the torso. These results are promising in using Nitinol® as a basis for wearable devices. A vibrotactile display, consisting of eight vibrating elements or tactors mounted in a driver's seat, was tested in a driving simulator by Erp et al. [42]. The results of the tests ran on participants that drove with visual, tactile, and multimodal navigation displays demonstrated that the tactile navigation display reduces the driver's workload, compared to the visual display, particularly in the high workload group. The fastest reaction was found with the multimodal display. It was concluded that a localized vibration or tap is an intuitive way to present directional information, and that employing the tactile channel may release other heavily loaded sensory channels, providing a major safety enhancement. The authors have also considered the use of a vibrotactile display in the cockpit [46].

Lindeman et al. presented the use of vibrotactile cues in the torso, as a mean of improving user performance on a spatial task [43]. The vibrotactile stimuli were delivered using tactors placed at eight, evenly spaced compass points around the torso of the participant. The tactors were positioned individually for each participant and held in place by pressure using a neoprene belt, forming a "TactaBelt". The tactors vibrated at a frequency of 142 Hz at 3.0 V and had a vibration quantity of 0.85 G. In a building-clearing exercise, directional vibrotactile cues were employed to alert participants exposed in areas of the building that were not cleared yet. Comparing the results with and without the use of vibrotactile cues, participants cleared more of the overall space when given the added vibrotactile stimulus. The average length of each exposure was also significantly less when vibrotactile cues were present.

On the other hand, Watanabe et al. developed a tactile device able to control the tactile sensation of surface roughness [47]. The device created a smooth tactile feeling by applying to the surface ultrasonic vibration with amplitude of a few micrometers. The sensation was controlled without altering the actual surface profile. Experiments, using five to 10 participants, showed a positive relationship between the generation of a smooth feeling and vibration amplitude, but dependence on vibration frequency. The typical perceived feeling with this method, "air smoothness", was postulated to be due to the "squeeze air film effect" between the finger and the surface. When the duration of the ultrasonic vibration was short enough, this method also enabled the generation of resistant impressions, such as "the surface is rougher/more sticky" and "a virtual protrusion exists on the surface".

3.1.2. Focused ultrasound

By focusing an ultrasound beam it is possible to directly stimulate skin receptors. In the field of medical science, Gavrilov et al. reported that short and intense ultrasound pulses caused somatic sensations of touch, warmness, coldness, and pain [21]. This report suggests that focused ultrasound is able to affect nerve structures directly and selectively.

An alternative is the use of radiation pressure generated by ultrasound to control precisely stress fields on the skin with high temporal and spatial resolution [48].

One advantage of using ultrasound for tactile display is the large frequency margin between the ultrasound and human tactile perception. If ultrasound higher than 1 MHz is used, the frequency is 1000 times larger than the bandwidth of tactile perception of 1 kHz. Therefore, if the quality factor of the ultrasound transmitter is smaller than 1000, it is easy to control the acoustic pressure with 1 ms resolution.

A second advantage is the spatial resolution, which is proportional to the wavelength of the signal. For example, for 5 MHz ultrasound, the wavelength in water is 0.3 mm.

A third advantage of using ultrasound to generate acoustic pressure is the elimination of problems due to contact. When the skin is stimulated mechanically, as in a pinhead-type tactile display, it is difficult to control precisely the contact condition and contact pressure because unexpected forces arise by the movements of the user's skin. However, by using ultrasound, the acoustic pressure on the skin can be easily controlled.

A device created at the University of Tokyo in 2004 was used as a platform for scientifically clarifying human tactile sensation and as a base for developing new applications of tactile information [49]. Using acoustic lens or linear phased arrays, focused radiation pressure, generated by Pumblum–Zirconium–Titanium (PZT) transducers, created tactile sensation in a specific circular area. The device consisted of a linear phased array using PZT, specifically designed and fabricated for high-power driving. Two different linear array transducer components (Nihon Dempa Kogyo Co., Ltd.) were used. One component had 10 pieces of 1 MHz PZT transducers arranged in a 1 mm pitch. The width of each transducer was 0.95 mm and its length 10 mm. The other component consisted of 30 pieces of 3 MHz PZT transducers arranged in a 0.5 mm pitch. The width of each transducer was 0.445 mm with a length of 10 mm. In both "10 piece" and "30 piece" components, each piece of PZT transducer was fixed on an aluminum bulk and thin backing materials were attached between the transducer and aluminum bulk. An acoustic impedance-matching layer was in contact with the front side of each transducer. A 2 gf total force was generated by using a 3 MHz ultrasound, modulated in 5 ms pulses, and by focusing the beam in a circular area of 1 mm diameter. The focal point was steered with the aid of the linear phased array, enabling the display to create various precise spatiotemporal patterns of pressure distribution on the skin [50]. The thresholds for inducing tactile sensations were estimated at 14 and 88 W/cm^2 for 1 and 5 MHz, respectively.

Direct receptor stimulation by ultrasound is also attractive. Selective stimulation to each mechanoreceptor will need frequencies as high as 20–100 MHz to localize the focal region three dimensionally. A 5 MHz ultrasound can be focused on the skin onto an area of 0.4 mm diameter in two dimensions. However, the localization along the vertical direction, as in selective stimulation to Meissner corpuscle and Merkel cells, will need a very high resolution, finer than 0.3 mm [48].

3.1.3. Surface acoustic waves

Nara et al. presented a tactile display using surface acoustic wave (SAW), which can continuously change the fineness of the surface's grain [51–53], and was based on the “Continuum Mechanics Model of Skin” developed by Phillips and Johnson in 1981 [25].

For their implementation, Nara et al. used the rapidly adapting characteristic of Meissner and Pacinian corpuscles. Based on an analysis of the physiology and function of the human finger, they mapped a one-to-one correlation of the displacements of the skin surface and the displacements of mechanoreceptors. Subsequently, a mapping from shapes of objects to the displacements of the skin surface was considered and shown to have a many-to-one correlation because of the mechanical response character of the skin. They proposed a tactile display using the many-to-one property of the mapping because the deformation of the finger surface, touching the amplitude-modulated elastic wave, is the envelope of the wave. This envelope is created by the superposition of the first longitudinal and the first flexural Lamb wave on the elastic plate. As the spatial frequency and the travelling velocity of the envelope are controllable, the arbitrary displacement of the finger surface and the arbitrary displacements of the mechanoreceptors can be formed. This methodology was later confirmed by an experimental device of silicon rubber vibrated by voice coils that generated an envelope wave [51].

Nara et al. proposed a tactile display based on the same basic principles as above but with a different implementation [51–53]. They stated that the requirements for tactile control, especially for stimulating the RA mechanoreceptors, can be achieved if the sources of shear stress: (i) are applied to the skin surface to create equivoluminal distortion detected by the mechanoreceptors, (ii) are spatially dispersed on the finger surface and, (iii) are temporally modulated with a stick–slip frequency determined by the parameters of the object to be displayed. Unlike other tactile displays which use stimuli perpendicular to the skin surface, they propose the use of SAWs to generate sources of shear stress that satisfy the above three requirements for tactile control.

The tactile display was implemented as a SAW device with a pair of Interdigital Transducers (IDT) on a piezoelectric substrate. The IDT is a digitlike- or fingerlike-periodic pattern of parallel in-plane electrodes used to build-up the capacitance associated with the electric fields that penetrate into the substrate. When voltage was applied to the contact pads, an electric field distribution was established between the spatially periodic electrodes and, because of the piezoelectric effect, an elastic strain distribution with periodicity was generated. The transducer operated with the highest efficiency when the excitation frequency was such that the physical distance between alternate lines corresponded to the wavelength of the surface wave. The SAW propagated in two opposite directions due to the symmetric structure of IDTs.

The device was fabricated on a 17 mm × 63 mm × 1 mm Lithium Niobate ($LiNbO_3$) 128-degree Y-cut substrate. Alternating voltage applied to an IDT generated a SAW. One of the prominent advantages of the display was the substrate’s thinness (1 mm) for creating stimuli to the finger. Interdigital transducers were placed at both ends of the substrate and a set of open-metal-strip arrays (OMSA) placed after the IDTs acted as reflectors. An alternating voltage was applied on one side of the IDTs in order to generate progressive waves. To generate standing waves, the voltage was applied to both sides of the IDTs. Users could explore the substrate with a slider. The slider has approximately 100 steel balls with a diameter of 800 m on a thin tape. The use of a slider was based on the following assumptions: (i) by pressing steel balls with the finger, a driving force can be effectively transmitted to the finger, (ii) steel balls can provide distributed points to which stress is applied on the finger surface, assuming that the tape is adequately thin and soft.

The principle for generating sources of shear stress that are distributed spatially and modulated temporally is as follows; when users explore the substrate without SAW and with their fingers (via the slider), kinetic friction by the substrate is applied to the steel balls, thus creating sources of shear stress which are distributed spatially on the finger’s surface at the position of each steel ball. By generating SAWs, however, the friction between the steel balls and the substrate is diminished because there is: (i) a decrease in contact time between the balls and the substrate, (ii) a squeeze-film effect by the air that exists between the balls and the substrate and, (iii) a parallel movement of the wave crest (only when using progressive waves). As a result, when either a progressive or standing SAW is generated in the substrate, shear stress on the skin becomes smaller than shear stress without SAW. Thus, by using a burst of SAWs, one can modulate the sources of shear stress applied to the skin surface using burst frequency. The moments when the wave suddenly appears corresponds to the moment when the stick state changes into the slip state as the friction suddenly decreases.

3.1.4. Electrorheological and magnetorheological devices

Electrorheological (ER) tactile displays [54,55], are a special class of mechanical devices that work with the aid of an ERF. Electric-field-induced changes in polarized dielectric fluid viscosity were originally noticed by Duff towards the end of 19th century giving rise to the term “*electroviscosity*” [56]. The addition of highly polarizable solid particles causes the resulting emulsion to undergo a liquid-to-semi-solid phase change upon the application of an electric potential. This was originally known as the Winslow effect [56], and is more commonly known today, as *electrorheology*. An ERF is defined as a colloidal suspension of a dielectric solid or polymeric particles (1–100 μm) in non-conducting solvents (the dispersed phase) and in an insulating base oil (the continuous phase), which under normal conditions behaves as a Newtonian fluid [57]. However, when subjected to an external electric field, the relationship between the viscosity of the activated ER fluid and the intensity of the applied electric field initially rises rapidly, often in a square law manner, until a field strength of several hundred volts per millimetre is reached. The applied electric field induces dipoles, oriented parallel to the field, in the dielectric particles. These dipoles interact in such a way that they align themselves along the field direction and the ERF transforms to semi-solid. Because of the large increase in viscosity and the rapid, reversible viscous response, technological applications have been proposed for ER fluids [58–64] in devices such as shock absorbers, clutches, valves, noise isolation, and vibration control. Likewise, medical applications in biomedicine have been investigated [65,66].

There are three possible modes of operation for ER fluids: shear, flow, and squeeze [54]. Though enjoying a wider dynamic force range, squeeze mode is limited to relatively small displacements. In flow mode, the motion of the ER fluid is controlled by electrostatic valves. In shear mode, two surfaces move against one another with the ER fluid controlled by the electric field between the two surfaces. The majority of the applications use fluids in shear mode, whereas the ER fluid in the tactile array is subjected to both shear and squeeze modes. When an element in shear mode is activated, the fluid layer above its surface stiffens and the passing probe experiences a significant horizontal and vertical force. Fluids used are 30% lithium polymethacrylate suspension in chlorinated paraffin (50LV series) and two silicone-based types: a polyurethane in silicone oil mixture (RHEOBAY®) and a silica compound in silicone oil suspension (ACTILIC 150.75®).

A detailed model and simulation of a tactile display using ER fluids was described by Klein et al. [67]. In 2005, they designed a very simple cylindrical "TACTEL" (TACTual ELement) [54]. The TACTEL comprised an electrically conducting cylindrical collar, which was electrically commutated by means of sliding contact with the sides of a cylindrical hole bored into a metal substrate normally held at ground potential. The hole contained the ER fluid and high voltage was applied to the central inner electrode. The authors have built a tactile display consisting of a 4 × 4 TACTEL array.

Similar to ER fluids, magnetorheological (MR) fluids are suspensions of micron-sized ferromagnetic particles dispersed in different proportions of a variety of non-ferromagnetic fluids [68]. Magnetorheological fluids exhibit rapid, reversible and significant changes in their rheological (mechanical) properties when subjected to an external magnetic field. As with ER fluids, the MR fluids are also in liquid state without external stimuli. When MR fluids are subjected to a magnetic field, they behave as solid gels, typically becoming similar in consistency with dried-up toothpaste. Recent MR fluids are becoming increasingly important in applications concerning active control of vibrations or switching/control of torque/force. A typical MR fluid contains 20–40% by volume of relatively pure, soft iron particles, e.g., carbonyl iron. These particles are suspended in mineral oil, synthetic oil or water. Magnetorheological fluids undergo a change in rheological behavior if an external magnetic field is applied. This significant effect is due to the induced magnetic polarization of particles within the fluids. Upon application of a magnetic field, the particles become magnetized and align themselves roughly parallel to the imposed magnetic field. The rheological properties of MR fluids are dependent on such factors as the mechanical and magnetic properties of magnetic particles, the viscosity of the continuous fluids, the proportions of each substance in the fluid, any additives, and the mixing process of the fluids. The design of a single MR fluid-based tactile element was described by Liu et al. [68].

3.2. Electrotactile stimulating devices

An electrotactile (also called electrocutaneous) display is a tactile device that directly activates nerve fibers within the skin with electrical current from surface electrodes thus generating sensations of pressure or vibration without the use of any mechanical actuator [10,31,69,70]. The electrocutaneous display can stimulate RA, SAI, and PC receptors individually. The mechanisms of electrical stimulation consider the control of the current distributed on skin surface and indirectly activate innervating nerve fibers. Activation probability can be considered as a function of current source distribution on the skin. The methods used for nerve stimulation are arrayed electrodes and single ones with the use of anodic and cathodic current.

Kajimoto et al. proposed an augmented reality system of cutaneous sensation, the SmartTouch® [10]. In the prototype system, a mounted optical sensor converted visual information from a contact object into tactile information. Electrical stimulation was employed to present tactile information. The tactile display was composed of a 4 × 4 matrix of stainless steel electrodes, each 1.0 mm in diameter. An electric current from the surface electrodes generated an electric field inside the skin, inducing nerve activity. The longitudinal and transversal interval of the electrodes was 2.5 and 2.0 mm, respectively. These intervals are determined by the fabrication limit due to the size of the optical sensor described below. The electrodes applied electrical current pulses of 1.0–3.0 mA with duration 0.2 ms to the skin (current controlled) in order to generate tactile sensation. Using short anodic and cathodic pulses they managed to selectively stimulate the Merkel cells (pressure sensation) and the Meissner corpuscles (vibratory sensation), respectively.

Studies concerning the two point discrimination of the system (using anodic pulse) showed that electrodes 2 mm apart are most frequently perceived as a short line, whereas those 4 mm apart are perceived as two distinct points [71]. Hence, the static resolution is 2–4 mm. On the contrary, conducting the same experiment using a cathodic current pulse, rather than the anodic pulse, the cathodic current pulse elicited a sensation that is typically blurred around the electrode, making it impossible to repeat spatial resolution measurements. Kaczmarek et al. [71] first observed this crucial difference. An electrophysiologic explanation proposed that a cathodic current activates nerve axons parallel to the skin surface. However, the brain mistakes the receptor connected at the axon tip as the one being activated. Therefore, a gap between the stimulation and sensation points always exists. The accumulation of this gap results in an unfocused sensation. This phenomenon is inherent to cathodic stimulation and cannot be avoided by a simple application with a coaxial electrode. On the contrary, an anodic pulse selectively stimulates vertical axons. Although the stimulation point and the connected mechanoreceptor might still have a gap, the gap is vertical so it has negligible influence on the sensation.

Tang et al. [70] proposed a polyimide-based flexible oral-tactile display with an array of 7 × 7 tactual actuators (*tactors*), for the presentation of electrotactile patterns onto the palate. The device was microfabricated on a rigid substrate using thinfilm and electroplating processes. Dome-shaped tactors were electroplated through round openings 300 μm in diameter in the flexible polyimide base for more uniform current distribution and better contact with the skin. The overall dimensions of the tactor array were $18.5\,\mathrm{mm}^2 \times 18.5\,\mathrm{mm}^2$, with a center-to-center spacing of 2.54 mm between adjacent tactors. Each tactor was 200 μm in height and 700 μm in diameter. The flexible oral-tactile display was tested in participants and found to deliver comfortable electrotactile stimulation with relatively low stimulation intensities.

In the eSmileys project [72], a game was developed with the Training and Testing Phase, in order to test the performance of a player in understanding the content of electrotactile patterns perceived by tongue. Ban used graphical images of emotions (smileys) as conditional semantic messages. The electrotactile patterns were used to alternatively display these pictographic images and associated information through parameters of the composite electrotactile patterns. An electrotactile converter and two software programs were designed for the eSmileys project.

4. Concluding remarks

In this paper we have reviewed the state-of-the-art of the technologies employed for tactile interfaces. In order to classify the actuators we have used the type of energy mediating in the activation of receptors. Of the three major categories (mechanical, electrical and thermal) we give emphasis in the first two. The mechanical actuators include static or vibrating pins, focused ultrasound, SAWs, ERFs and MRFs, while the electrical devices use current flow or electric field. Most of the research and the applications have focused on the "pin" concept, either static or vibrating. Although, there are many advantages such as design flexibility and better resolution, electrotactile, focused ultrasound, SAW, ERF and MRF devices have seen publicity only in the recent years due to difficulties in fabrication and integration.

In general there is an increase in volume of the published work, concerning tactile displays, as the scientific and industrial community recognize the many potential applications for the sensory impaired, education, consumer electronics, biomedicine, robotics and military.

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