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Review

A review of tactile sensing technologies with applications in biomedical engineering

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ABSTRACT

Any device which senses information such as shape, texture, softness, temperature, vibration or shear and normal forces, by physical contact or touch, can be termed a tactile sensor. The importance of tactile sensor technology was recognized in the 1980s, along with a realization of the importance of computers and robotics. Despite this awareness, tactile sensors failed to be strongly adopted in industrial or consumer markets. In this paper, previous expectations of tactile sensors have been reviewed and the reasons for their failure to meet these expectations are discussed. The evolution of different tactile transduction principles, state of art designs and fabrication methods, and their pros and cons, are analyzed. From current development trends, new application areas for tactile sensors have been proposed. Literature from the last few decades has been revisited, and areas which are not appropriate for the use of tactile sensors have been identified. Similarly, the challenges that this technology needs to overcome in order to find its place in the market have been highlighted.

Contents

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1. Introduction

As humans, we utilize our vision, touch, taste, smell and sound sensory receptors as a means to experience and interact with the surrounding environment. Exploiting one or a combination of these senses, humans discover new and unstructured environments. For example, as humans, the ease with which we perform dexterous tasks, such as manipulating an egg, is taken for granted. When manipulating an egg, the shape, size, temperature, color and texture are transmitted to the brain from the sensory receptors. If the applied force is too little, the egg slips. Contrarily, if the force applied is too great, the egg will break. A precise force is applied and constant feedback of the measured applied forces keeps the egg intact. In addition, *a priori* knowledge of the egg's physical attributes, such as its weight and fragility are also integrated into the cortical processing used for the manipulation task. If the same task is to be achieved using a robotic manipulator, sensory inputs similar to those possessed by humans are essential to provide the necessary feedback to explore and interact with objects. Given that a robotic manipulator is unlikely to possess contextual *a priori* information about the object being manipulated, accurate sensory feedback is even more critical.

1.1. What is tactile sensing?

This paper reviews artificial research in the field of tactile sensor design. Tactile sensors are a category of sensors that acquire tactile information through physical touch. The measured characteristics can be properties such as temperature, vibration, softness, texture, shape, composition and shear and normal forces. A tactile sensor may measure one or more of these properties. Although pressure and torque sensing is often not included in the definition of tactile sensing, pressure and torque are important properties, typically acquired by physical touch, and can be included as tactile parameters.

1.2. Scope of tactile sensing technology

The maturation of tactile sensing technology has been anticipated for over 30 years. Early researchers such as Harmon, saw huge potential and application of tactile sensing in areas of robotics [1–3]. It is interesting to mention that Harmon considered tactile sensing unfit for areas such as medicine and agriculture because of technical difficulties and low return on investment [4]. In the same time, other researchers such as Nevins and Whitney argued that passive monitoring will eliminate the need of tactile sensing [5]. Around the start of the 21st century, it was envisioned that this technology would have the potential to support the development of more intelligent products and systems and hence improve the quality of human life [6,4]. At the top of this list of applications were medical robotics and industrial automation [6]. It is the belief of the authors that the scope of this technology is much wider and spans across many other disciplines, as discussed later in Section 4.5 of this review and summarized in Table 6. This survey will show, however, that this technology failed to gain significant entry into many of its target markets, either industrial or commercial, until the 1990s. The importance of tactile systems becomes apparent in applications where other sensing modalities, such as vision for example, may not be the best sensing modality; especially in unstructured or space-limited scenarios, as discussed later. Although particular importance and effort has been put into the development of tactile sensors over the past three decades, a satisfactory artificial tactile sensor that can provide feedback matching the human sense of touch has not yet been realized and in turn limits progress in fields such as robotics and minimally invasive surgery [7–12].

1.3. Earlier technological reviews

Force and tactile feedback research is currently a multidisciplinary enterprise [13]. Comprehensive surveys of tactile sensor

technologies have been performed in the past and are available in the literature. Some of the earliest surveys were carried out by Harmon in 1980 [3], 1982 [1] and 1984 [2]. Tactile sensing for robotics and mechatronics applications have also been reviewed and reported in the literature [6,14–19]. In 2000, Lee published a short, yet comprehensive, review on tactile sensing technology and analyzed the causes of delayed acceptance of this technology among industrial and consumer markets [4]. In 2003, Eltaib and Hewit examined tactile sensing systems for minimally invasive surgery and reasserted the importance of the technology for this particular field [20].

Although a number of books written on robotics and sensors cover tactile sensors, not many books have been written on tactile sensors alone [21–25]. A few noteworthy books have also been published on tactile sensing. Wettels in his book [26], demonstrated how sensor can mimic human skin. One of the most comprehensive book on tactile sensing for biomedical applications was published in 2009 by Najarian and Dargahi [27]. The book encompasses the basics of human tactile sensing, intrinsic sensing technologies and applications in areas of biomedical engineering.

In comparison to previous reviews of tactile sensing technology, this paper extends previous reviews by focusing on the current state-of-the-art in the discipline, trends in tactile sensor research, outstanding challenges which must be overcome, principles of operation and advantages and deficits of different tactile sensor designs are also discussed. We also propose additional applications of this technology, in the fields of recreational sport, aerospace engineering, automotive manufacture and rehabilitation medicine, in addition to the previously explored fields.

We start with a overview of some common tactile sensing transduction techniques.

2. Tactile transduction techniques

Some commonly researched tactile transduction techniques are based on capacitive, piezoresistive, thermoresistive, inductive, piezoelectric, magnetic and optical methods. The intrinsic principles associated with these techniques have their own advantages and disadvantages, which are well established [27,28]. In general, capacitive, piezoresistive, piezoelectric, inductive and optical methods show a potentially superior performance and usefulness and are often the preferred choice of sensor designs. In this section, we give a brief review of these methods and their relative advantages and disadvantages; these are also summarized in Table 1.

2.1. Capacitive tactile sensors

A capacitive sensor consists of two conductive plates with a dielectric material sandwiched between them. For parallel plate capacitors, capacitance can be expressed as, $C = (A\varepsilon_0\varepsilon_r)/d$. Where C is the capacitance, A is the overlapping area of the two plates, ε_0 is the permittivity of free space, ε_r is the relative permittivity of the dielectric material and d is distance between the plates. Capacitive tactile sensors generally exhibit a good frequency response, high spatial resolution, and have a large dynamic range. These sensors are more susceptible to noise, especially in a mesh configurations because of crosstalk noise, field interactions and fringing capacitance and require relatively complex electronics to filter out this noise.

2.2. Piezoresistive tactile sensors

These sensors typically consist of a pressure sensitive element which changes its resistance upon application of force. The voltage–current characteristic of a simple resistive element can be expressed as, $V = IR$; where V is the voltage, I is the current and R is the electric resistance of the material. Usually some property of the voltage (or current) is fixed and a change in resistance is observed by a change in the current (or voltage). This resistive element generally takes the form of a conductive rubber, elastomer, or conductive ink which is pressure sensitive. They generally require less electronics as change in resistance can easily be quantified and are therefore easy to manufacture and integrate. They are less susceptible to noise and therefore work well in mesh configurations as there is no cross talk or field interactions. Resistive tactile sensors suffer from hysteresis and therefore have a lower frequency response when compared to capacitive tactile sensors.

2.3. Piezoelectric tactile sensors

Various materials, especially certain crystals and some ceramics, generate a voltage potential when the crystal lattice is deformed [10,11]. The sensitivity of the crystal depends on its cut/structure, allowing it to distinguish between transverse, longitudinal and shear forces. The voltage, V, generated is directly proportional to the applied force, pressure or strain. These sensors exhibit a very good high-frequency response, which makes them an ideal choice for measuring vibrations; however, they are limited to measuring dynamic forces and are unable to measure static forces due to their large internal resistance. The charge developed decays with a time constant which is determined by the internal impedance and dielectric constant of the piezoelectric film. During sensor design, the input impedance of the interface electronics must be considered as it significantly effects the response of the device.

2.4. Inductive tactile sensors

A primary coil induces a magnetic field which is sensed in a secondary sense coil. Modulating the mutual inductance between the coils, for example by changing the length of an iron core in the case of a linear variable differential transformers, in turn modulates the amplitude and phase of the voltage measured in the sense coil. These sensors have a very high dynamic range and an often rugged construction, but are bulky in size, which leads to a very low spatial resolution when arrayed. Due to their mechanical nature, they have lower repeatability as coils do not always return to the same position between readings. Since these sensors use an alternating current in the primary coil, hence producing an output voltage at the same frequency, they require more complex electronics than normal resistive tactile sensors as the alternating signal amplitude must be demodulated.

2.5. Optoelectric tactile sensors

Optoelectric sensors employ a light source and a transduction medium and a photodetector, the latter often in the form of a camera or a photodiode. Usually transduction occurs when changes in the tactile medium modulate the transmission or reflectance intensity, or the spectrum of the source light, as the applied force varies. They have high spatial resolution, and are immune to common lower frequency electromagnetic interference generated by electrical systems, which is their major advantage. Although they have many benefits, their size and rigidness are major disadvantages. Camera-based tactile sensors require considerable processing power but give a wide ranging frequency response.

2.6. Strain gauges

Strain gauges are widely used, low cost sensors that measure mechanical strain, typically by a change in resistance [29]. Strain gauges are often attached to the substrate using special glues,

Table 1
Transduction techniques and their relative advantages and disadvantages. For in depth discussion on these techniques, refer to [27,28].

Transduction technique	Modulated parameter	Advantages	Disadvantages	Typical design examples
Capacitive	Change in capacitance	Excellent sensitivity Good spatial resolution Large dynamic range	Stray capacitance Noise susceptible Complexity of measurement electronics	[41–47]
Piezoresistive	Changed in resistance	High spatial resolution High scanning rate in mesh Structured sensors	Lower repeatability Hysteresis Higher power consumption	[48–53]
Piezoelectric	Strain (stress) polarization	High frequency response High sensitivity High dynamic range	Poor spatial resolution Dynamic sensing only	[54–60]
Inductive LVDT	Change in magnetic coupling	Linear output Uni-directional measurement High dynamic range	Moving parts Low spatial resolution Bulky Poor reliability More suitable for force/torque measurement applications	[61–67]
Optoelectric	Light intensity/spectrum change	Good sensing range Good reliability High repeatability High spatial resolution Immunity from EMI	Bulky in size Non-conformable	[68–74]
Strain gauges	Change in resistance	Sensing range Sensitivity Low cost Established product	Calibration Susceptible to temperature changes Susceptible to humidity Design complexity EMI induced errors Non-linearity Hysteresis	[38,75–77]
Multi-component sensors	Coupling of multiple intrinsic parameters	Ability to overcome certain limitations via combination of intrinsic parameters	Discrete assembly Higher assembly costs	[31,32,36,37]

depending on their required lifetime. Strain gauges are very sensitive and highly susceptible to humidity and temperature changes. To overcome these problems, strain gauges are often used in Wheatstone bridge configurations [30]. If overloaded, strain gauges cannot be recovered. Due to their mechanical nature, they have high hysteresis and often are non-linear in response. One major advantage of strain gauges is that they have been widely used for a long time and therefore best practices for their use are well established.

2.7. Multi-component tactile sensors

Combining multiple different transducers in one sensor to overcome the shortcomings of each different devices has also been investigated by several researchers [31,32]. For example, a PVDF (polyvinylidene fluoride) film can only detect dynamic forces and has a well established ability to detect slip [33–35], but cannot measure static forces. This limitation can be overcome through the addition of a resistive or capacitive element, and thus making a slip and static force detecting sensor [31,32,36,37]. For applications where flexibility or large area coverage is a requirement, fluid based tactile sensors are commonly used, combining various intrinsic methods to achieve the task [38–40].

3. Past trends and advancements

In this section, research and development trends and advancements are presented, from emerging applications to commercialization of tactile sensors. A steadily increasing trend in research and demand can be seen in both academic (Table 2) and commercial sectors (Table 3).

3.1. Inception in the 1970s

A detailed survey of related research in the 1970s was performed by Harmon [3,1,2]. Although these surveys covered 160 papers, a careful review of the references reveal that most of the papers addressed other sub-areas of robotics rather than directly contributing to tactile sensor technology [4]. For example, it was realized that if robotic grippers could handle soft, fragile and hard objects, robots could be used in a broader range of fields, such as manufacturing industry, military weapon systems, medical treatments and agriculture [78]. Hence to develop better grippers, some researchers developed tactile sensors or tactile sensing mechanisms [78–82].

3.1.1. Major contributions

As stated above, although tactile sensing was not a mainstream research area, the use of tactile sensors in products to improve quality of human life, especially in the field of biomedical engineering, resulted in some cutting edge outcomes.

For example, Pfeiffer et al. took the challenge of developing a prosthetic device intended to overcome neuropathy of the hand that can result from injury or disease [83]. Neuropathy of the hand is a very severe, untreatable condition, as the patient is always

Table 2
Count of papers per decade, starting in the 1970s, using the search terms “tactile AND sensor” grouped by decade.

Year	Scopus	IEEE	Compendex	SPIE Digital Library	Springerlink
1970–1979	47	4	42	–	0
1980–1989	536	97	480	–	8
1990–1999	647	342	607	40	117
2000–2009	1341	675	1132	70	1709

Table 3
Count of patents filed, grouped by decade, using the search terms "tactile AND sensor".

Year	US Patents		European Patents		Japanese Patents	World Intellectual Property Organization (WIPO)
	Scopus	Compendex	Scopus	Compendex	Scopus	Scopus
1970–1979	84	4	–	–	3	2
1980–1989	377	45	102	29	69	36
1990–1999	1281	91	411	77	107	570
2000–2009	11772	447	969	229	107	2291

in danger of accidental self-inflicted injury due to the absence of sensation, including pain. The prosthetic device was intended to provide haptic feedback to such patients using tactile sensors worn on fingers. The flexible pressure sensors used a mercury strain gauge. An signal generator emitted an audible sound whose frequency was modulated as a function of pressure. Although the device had several limitations, such as signal distortion, it gave patients the ability to differentiate between no force and modest forces. Pfeiffer et al. concluded that tactile sensors held the potential to ease the disability of neuropathy, but much work was needed before such devices could become standard prosthetic aides, as it only gave an indication of the presence of force, rather than its magnitude.

In a similar effort, Shaw et al. used tactile sensors in myoelectric upper limb prostheses to provide electrocutaneous feedback to the wearer [84]. Stojiljkovic and Clot took their efforts one step further and tried to detect slip in upper limb prostheses [85]. They covered a hand prostheses with planary distributed transducers and called it "artificial skin". This artificial skin consisted of deformable elastomer electrodes, covered with a superior conductive layer, to which a voltage was applied. Upon application of force, the resistance of the elastomer electrodes changed. Experimentation showed that tactile sensors could be used to provide slip perception of the grasped objects in prosthetic grippers. But at that time it was not possible to measure the elasticity of materials using these tactile sensors [86].

One impressive development was reported by Kinoshita et al. [87]. In an attempt to develop pattern classification methods for systems utilizing visual and tactile sensors, a tactile sensor array using piezoelectric sensing elements was developed and integrated in a robotic hand. With the aid of a pattern classification model, the device was able to discriminate between cylindrical and square pillars. Kinoshita et al. concluded that for stereometric pattern recognition, a visual-tactile symbiotic system was more practical and efficient than conventional methods [87].

3.1.2. Advancements and achievements

The work in the 1970s laid the cornerstone of tactile sensing research. The research outcomes in this period were understandably primitive, but by the end of this decade tactile sensing was recognized as a field of study that had the potential to address many engineering problems associated with robotic manipulation.

3.1.3. Hurdles and challenges

By end of the 1970s a number of challenges remained. Although the need for tactile sensing technology was accepted by many, and some success was achieved in demonstrating its feasibility to solve real life problems, as discussed previously in Section 3.1.1, tactile sensing was often reported as a minor area of research within a major project. The main reason was that robotics and computers were starting to gain the interest of research and funding organizations, as research in these fields was still in its embryonic stages but obviously offered great returns on investment [4]. It is therefore fair to state that tactile sensing was a minor interest, secondary to what would become a feverish interest in developing sophisticated, reliable and faster robotic and computer systems. A second but inevitable impediment to progress was immaturity of the field, as many tactile transduction materials were yet to be discovered. Lastly, research was lacking direction and focus, as no design criteria had ever been specified, taking into consideration the industrial or biomedical engineering needs at the time.

Ultimately, researchers did demonstrate that this field of tactile sensing had the potential to investigate a number of unsolved problems and therefore deserved attention as a mainstream research area.

3.2. Evolution in the 1980s

A major step in highlighting the significance of tactile sensing technology and its possible applications was taken by Harmon in 1980 with his review [3]. The potential of this technology was further emphasized by two more papers which followed shortly afterwards [1,2]. The unavailability of any design criteria was still a major obstacle to progress. Harmon also attempted to specify design criteria for tactile sensors. He surveyed the industry with a set of questionnaires and interviews and based his design criteria on the desired sensor parameters required by the respondents at that time. Harmon proposed that a spatial resolution of 1–2 mm, frequency response of up to 100 Hz, a minimum sensitivity of 1 g and a preferably monotonic relationship between the sensor output and the force applied, were preferred characteristics of most tactile sensors. Later, Lee summarized this criteria, shown in Table 4 [4].

3.2.1. Motivation and research direction

The primary research objective in the 1980s was to develop reliable tactile sensors for robotics. Harmon's proposed design criteria were often used by researchers to justify their research direction [4]. Development of tactile sensors for medical devices, as described in Section 3.2.2, was the second major area of interest.

Due to the coupling of biomedical and tactile sensing technologies, an important outcome was the inspiration to develop sensors and materials which could mimic the response of mechanoreceptors in the human skin [88,89]. Rossi felt that the tendency of researchers to develop sensors which mimic the human tactile system was placing unnecessary restrictions on sensor requirements, as the human tactile system may not be the universal solution to tactile sensing [28]. Rossi believed that every design problem has its own set of challenges and constraints, and advocated the need for different specifications and design requirements.

Table 4
Design criteria proposed by Harmon [3] and later summarized by Lee [4].

Sensing surface	Complaint and durable
Spatial resolution between sensing points	1–2 mm
Number of sensing points in an array	Between 50 and 200
Minimum pressure sensitivity	1 g
Dynamic range	About 1000:1
Output response	Monotonic, not necessarily
Frequency response	At least 100 Hz
Stability and repeatability	Good
Hysteresis	Low

3.2.2. Advancements and noteworthy contributions

Research trends to this date had been device-driven rather than task or application-driven [4]. It was hoped that these devices would find application in the market upon development; although very few, if any, reached the market or became part of other systems. This survey indicates that work in this decade did move towards application driven designs. Attempts were made to solve real problems such as overcoming birth injuries [90,91], orthoses for the disabled [92,93], development of a portable terminal for the blind [94], and as an aid for neuromuscular control [95]. The research outcomes were often not deployed in real world medical applications due to the regulatory constraints required before new devices could be used in clinical settings.

Another novel research area was the development of an audio-tactile device for the blind, with the aim to improve the accessibility of stored information for blind people [93]. The device enabled the vision impaired to read data stored in computer memory. The system consisted of a multi-touch tactile sensor, data memory unit and a voice synthesizer. By touching a point on the tactile sensor, the corresponding data in memory was synthesized. Although it was a very promising design with an actual need in real life, the design was limited by the lack of technological advancements in data storage and data acquisition devices.

One state-of-the-art tactile sensor array, based on a very large scale integration (VLSI) computing array, was developed in the 1980s [96]. The force transduction was performed using conductive rubber and metal electrodes assembled on the surface of the purposely built integrated circuit. The use of VLSI technology led to an integrated, low wire count, serial output and high resolution sensor array which could operate at very high speeds. The most important contribution of this research was the introduction of arrayed, high speed and high spatial resolution concepts in tactile sensing technology. The high cost of VLSI-based designs kept this approach within the confines of the laboratory, with little adoption by industry.

3.2.3. Limitations and challenges

Although some researchers tried to test tactile sensors in real world environments, both in the disciplines of robotics and biomedical engineering, these efforts were limited. The main advancement in this decade was the exploration of different transduction techniques and the collation of the relative advantages and disadvantages between these techniques. The high cost of manufacturing small-scale designs (both electrical and mechanical) and high computational costs were major technological constraints preventing advancement.

By the end of the 1980s, major advancements in low cost manufacturing and computational capabilities were occurring, which would lay the foundations for progress in subsequent years. For a detailed review of transduction techniques explored in this time, and pros and cons established, refer to [97,28]. For a detailed review of this decade, refer to the review by Nicholls and Lee [16].

3.3. Developments in the 1990s

By the end of the 1980s, with advancements in computational processing power, realization of complex and real time algorithms became possible. Characterization and discrimination algorithms became a new area of interest.

As shown in Tables 2 and 3, an increased interest in this technology is evident. But a shift in the interests of researchers was also evident. Lee reported a shift towards softer, natural systems, away from constrained, solid-materials of the industrial arena [4].

3.3.1. Demand and motivation

During this period, Nicholas and Lee reported on sensor design and construction, haptic and active perception, and analysis and experience, as the three major areas of research in tactile sensing [6]. Lee reported better engineering and new materials, the increased importance of the understanding of sensors, improved dexterous robotic hands and new medical applications as the notable areas of development in the 1990s [4]. However, due to lack of penetration of this technology into industrial applications, the focus of research changed from industrial to unstructured domains [6].

3.3.2. Emergence of new problems, challenges and application areas

A major highlight of this era is the application of tactile sensing in minimally invasive surgery (MIS). The term MIS was first coined by Wickham in 1984, and later published in 1987 [98]. MIS, also known as endoscopic surgery, is considered to be one of the biggest success stories in medical history [99]. But this technology is somewhat limited by restricted mobility, lack of perception of depth and minimal tactile feedback [100]. Some notable attempts to apply tactile sensing in endoscopic surgery have been reported [101–107].

A sophisticated optical tactile array of 64 measurement points on a 0.64 cm^2 surface area was presented by Fischer et al. [108]. The sensor was conceived to be integrated in the laparoscopic grasping forceps, while the measured values activated a vibrotactile display unit for tactile feedback to the surgeon's fingertip. Another important development was that of a tactile sensor for thoracoscopic detection of small and invisible pulmonary nodules [109]. This sensor was first tested on pigs, followed by clinical testing on humans, showing that tactile sensing is not just a laboratory technology but can be used to solve real life challenges.

Rehabilitation and service robotics concept designs also began to emerge, motivated by concerns for aging populations and to improve quality of life for the disabled. For service robots, especially those which are intended to assist elderly or disabled people, the robot's ability to interact with a changing environment is of critical importance. This calls for dexterous robots with intelligent sensors.

This need for tactile sensing to overcome the challenges associated with useful functioning of service robots in uncontrolled environments was realized in the early 1990s. Keane and Greg highlighted that although further research in tactile sensors is required in order to develop robust, economic and general purpose sensors, there are a number of applications where information is best acquired by tactile means [110].

For such robots, Hohm et al. suggested rule-based behavior to autonomously plan navigation, using mainly tactile sensor information [111]. Seitz integrated vision and tactile sensing to overcome the limitations of using vision systems in unstructured environments [112]. Their research showed that vision and tactile sensors can be integrated into the hands/manipulators of service robots to assist humans in industrial or service environments. A significant attempt was made by Ueno and Haruki to develop an autonomous anthroposophic service robot (HARIS) [113]. The five fingered robot had 178 tactile sensors.

Although, industrial service robots have been a success, service robots capable of working in unstructured environments have not yet been realized. Research in this area not only explored the benefits of research to develop service robots, but also provided motivation for further research.

3.3.3. Advancement and limitations

Research in this period led to an increased demand for the application of tactile sensing in the fields of food processing,

automation and biomedical engineering. Increased spatial resolution was achieved, which lead to surface texture profiling and hardness characterization. Piezoelectric elements and arrays of capacitive and resistive elements evolved as the preferred choice of transduction. Integrated circuit devices were also fabricated which helped to miniaturize the sensor systems. Analysis of effects of elastomer skins on tactile sensor responses, the dynamics of slip and a deeper understanding of human tactile sensing were also reported. For a detailed survey of this period, refer to reviews by Nicholas and Lee and Lee [6,4].

3.4. Recent advancements in the 21st century

Both research and commercial sector have recently begun to direct their attention towards tactile sensing technologies, as evidenced by Tables 2 and 3. Tactile sensing is finding its place as a feasible technology and is enhanced by advancements in computation, fabrication methods and materials. The limitations of vision systems have also been established and calls have been made for the development of novel sensing systems, especially for space confined and/or unstructured environments [114,112].

In contrast to the 1970s and 1980s, when the motivation for research in tactile sensing technology was primarily to develop intelligent robotics, the main motivation today is to develop systems for biomedical applications and tactile sensing systems for unstructured environments. Some of these applications of tactile sensing in biomedical engineering and robotics are discussed below.

3.4.1. Minimally invasive surgery

The state-of-the-art in force and tactile sensing for MIS has recently been reviewed [115]. Although the benefits of MIS technology have been proven, the limitations of two-dimensional visualization, lack of haptic feedback and long learning times are their limiting factors [116–118].

Haptic feedback refers to restoring sense of both tactile and force information [119]. The need for restoration of haptic touch has increased; especially due to the expectations of tele-robotic systems in general, and MIS in particular. Although force feedback is provided in the da Vinci surgical system (Intuitive Surgical Inc., USA) to compensate for lack of a tactile sense, having tactile feedback would enable analysis of tissue characteristics and pathological conditions. Similarly, force feedback allows detection of collisions with rigid structures but does not prevent damage to soft tissues or tearing of sutures [120]. These limitations can be overcome with a haptic feedback system. Furthermore, haptic feedback using visual and auditory cues may prove distracting during surgeries, hence haptic feedback is preferable [121].

A number of attempts aiming to provide haptic feedback for MIS have been reported. Force feedback systems have been developed [122–127] and are useful as a partial replacement for complete tactile feedback. Studies have indicated a reduced application of force by a factor of 2% to 6%, a 30% to 60% reduction in RMS force, 60% less errors, and a faster surgery completion time by 30% [128–130]. Although visual systems do provide limited feedback, providing both vision and force feedback leads to better tissue characterization [131].

Attempts have also been made to develop systems which provide comprehensive tactile feedback for MIS. Cultaj et al. developed a pressure stimuli system for the da Vinci surgical system. Mechanoreceptors were stimulated using a pneumatic array of 3 mm inflatable balloons [132–134]. Human psychophysics tests performed with this actuator demonstrate the effectiveness of the 3 mm diameter balloon in providing effective haptic input to the human sensory system, by stimulating the finger mechanoreceptors.

During classical surgeries, surgeons often use their hands to estimate how much force should be applied so that the surrounding tissues are not damaged [27]. Similarly, to detect arteries, surgeons use their hand to sense a time varying pressure [135–137]. Another important tactile assessment is to differentiate between a normal artery and a stenotic artery, which is often done by palpation or rolling between the fingers [135,136]. Although artery detection is not possible in MIS at this time, progress has been made to over come this limitation [138–140].

Besides tumor and artery detection, due to lack of tactile feedback in MIS, detection of kidney stones and determining their exact location is not possible [141]. In order to remove stones, methods such as extracorporeal shock wave lithotripsy (ESWL), percutaneous nephrolithotomy (PNC), open surgery and in some cases MIS are employed, based on size of kidney stone [142]. Some recent conceptual simulation studies have shown that detection and localization of kidney stone is possible [143–145].

Despite increasing interest from researchers in developing tactile sensors for MIS, the employment of these sensors in developed systems has been minimal. However, it is important to consider that the da Vinci surgical system, shown in Fig. 1, is the only master–slave MIS system, approved by US Food and Drug Administration (FDA). The system has been successfully used for general, urological, gynecological, thoracoscopic, and thoracoscopically assisted cardiotomy procedures. The system provides force feedback and a 3D vision, but lacks feedback of tactile sensation.

Designing tactile sensors for MIS tool ends still remains an unsolved problem. Commercial robotic surgery systems currently use a tactile feedback system and the alternative visual and force feedback systems have many limitations. Although many sensors that are able to detect shear and tissue characteristics have been developed, not all are biocompatible, robust, miniature and do not hinder tool movement. Easy assembly/disassembly and cost are also major challenges due to the disposable nature of these sensors.

3.4.2. Tissue elasticity and palpation characterization

Tissue elasticity and palpation are important parameters used by surgeons to assess the quality of soft tissues and to find tumors and arteries in the human body. In clinical practice, doctors often use the hand and palm to assess the condition of organs and tissues. Although this is a useful method of diagnosis, doctors often miss nodules and small lumps [146]. The issue of improving the qualitative nature of palpation characterization has received considerable attention in recent times, as indicated by Hall et al. [147], and recently reported devices [148–152].

Since palpation characterization and detection of tumors and arteries share many goals with MIS and haptic feedback, advancements related to these fields are not discussed here, as they have already been discussed in previous sections.

Palpation is often used to detect breast cancer at an early stage. Methods such as clinical breast examination (CBE), ultrasound, mammography, magnetic resonance imaging, and biopsy are already in use. Tactile sensing devices are currently being developed and tested. Almost 70% of cancer deaths occur in low or medium earning countries, because of lack of healthcare resources [153,154]. Therefore, efficient yet low-cost diagnosis systems for breast cancer are required [155]. A comparison of all the available methods, shown in Table 5, indicates that tactile based diagnosis systems have the potential to provide an effective, low-cost solution [156].

A device called SureTouch (Medical Tactile Inc., CA, USA) has demonstrated up to four times more sensitivity than the human hand in finding breast tumors during clinical examination [157]. Currently the device consists of 192 high resolution pressure sensors that mimic the human sense of touch. The device detects changes in elasticity caused by developing lesions. This change in

Fig. 1. The da Vinci surgical system. The surgeon operates while seated at the master console. Tools are controlled by translating the surgeon's hand, wrist and finger. Reproduced with permission © 2010 Intuitive Surgical Inc.

elasticity is then used to indicate masses or lumps in the breast, which are displayed as 2D and 3D images. Due to high sensitivity, SureTouch claims to detect lumps or masses as small as 5 mm, which cannot be felt by human touch. It is worth noting that this claim does not agree with other studies where sensitivity of CBE was shown to be 56.5%. A similar device called palpation imaging has shown a positive predictive value of 94%, compared to 78% for physical examination [158]. There is scope and need for further research in this area.

3.4.3. Tactile pattern recognition

Almost all biological creatures, including human beings, explore and interact with their environment using biological sensing systems including touch. While physiologists report a better understanding of human tactile physiology, microelectronics attempts to mimic the physiological structure. The area has also attracted an increased interest from researchers in computer sciences. This interest has led to research in areas of tactile pattern classification.

Gait analysis is a primary means of identifying walking disorders in people, and for monitoring results of rehabilitation treatment. Generally, these tests are performed with the help of a camera and force–plate systems. Besides the small area of the force plates being a limitation, some patients have been observed to target and strike the plate abnormally hard, creating false readings [165]. The acquired data is large and is often analyzed manually by experts [166]. Recently, a replacement of force plates with tactile based sensors has been proposed [167]. The tactile sensing plate acquires data only from the area of contact and hence greatly reduces the amount of data that must be processed, allowing automation of the data analysis.

An important parameter in service and exploratory robots is to distinguish between different textures and materials. Mazid and Ali used optical tactile sensors to acquire data from different objects such as a carpet, stone, rough sheet metal, a paper carton and a table surface [168]. Similar studies have also shown that texture classification can be performed using inexpensive tactile sensors [169–173].

3.4.4. Tactile sensors for prostheses

Measurement of how prostheses fit during motion can also be estimated using tactile sensors. For prostheses, the fit at the stump-socket interface is critical. Unconformable fitting leads to over-stressing, pistoning, shear induced ulcers and ultimately future amputations [174,175]. Furthermore, the problem becomes

Table 5
Comparative data for breast cancer detection and cost effectiveness [156].

Screening/diagnostic technique	Sensitivity/specificity, %	Procedure cost of bilateral exam, USD	Cost-effectiveness, USD per life year gained
Clinical breast examination	56.5/93.7	–	522, India [159] 31,900, Japan [160]
Mammography	73.7/94.3	112*	1846, India [159] 26,500–331,000 [161]
Ultrasound	Limited, see [156]	70*	–
MRI	87.7/92.8	1037*	55,420–130,695 [162]
Biopsy	96.6/100.0	2061***	2250–77,500 [163,164]
Elasticity imaging	95.1#/100.0	–	–
Tactile imaging	91.9##/88.9	5–50***	162***

* The US average Medicare reimbursements in 2005.
*** Projections based on a physician's assistant performing the exam.
\# Averaged for nine clinical studies.
Averaged for two clinical studies.

more severe in patients with diabetes because of slow or limited healing of wounds and ulcers [176–178], which might be caused due to unconformable fitting. Generally, custom-made limb fittings rely on static measurement of residual tissue mechanics and topology; however, static measurement of the fit will not adequately predict the severity of the aforementioned conditions. Efforts are being made to overcome this problem using tactile sensing technology [179–182].

Another important utility of tactile sensing technology is to provide feedback in prostheses. Managing aspects of object manipulation, such as the amount of force or torque applied during object manipulation, or the force and position information acquired by mechanoreceptors of the foot during walking, are trivial for able-bodied people. Acquiring such information from prosthetic limbs is challenging. Attempts have been made to overcome this challenge using visual, auditory, electrical, tactile and vibrotactile stimulation [183–189]. Although each of these modalities have their advantages and disadvantages, but electrical and tactile sensing have proven to be most effective [185].

3.4.5. Recent advancements

Advancements in data processing and computational technologies have given researchers the opportunity to seriously pursue the work of researchers of the 1970s and 1980s. For example, Burger et al. have worked to develop a compact electronic module for non-visual display of alphanumeric data, that was previously hindered by limitations in data storage and data acquisition devices [93]. Efforts to develop wearable, tactile-based Braille reading devices have since been reported [190–194].

A major success of this technology is seen in smart phones. Tactile sensors have enabled the users to quickly browse through content on a small screen accepting high resolution tactile input commands. However this area is beyond the scope of this review.

3.4.6. Obstacles and challenges

With the demographics of many societies increasing in age, the need for automated production lines, improvement of human lives with prosthetic devices, acceptance of robotic surgery systems in hospitals, increased popularity of touch-based commercial and home products, a tremendous amount of responsibility has shifted to the shoulders of researchers working in the area of tactile sensing. With the need for reliable and smarter tactile sensing solutions, the amount of research in the area does not seem to be enough. Since the technology failed to gain prominence in either commercial or industrial markets for almost two decades, it needs to undergo a re-evaluation. This review is one such effort reflecting on the possible application and value of such technologies.

4. Reasons for delayed acceptance of tactile technology

4.1. Overoptimistic prediction

Although Harmon's work was significant in terms of realizing the importance of design criteria for tactile sensing technologies, his predictions for the success of this technology was seen as overoptimistic until 2000 [4]. By the end of the 20th century very few, if any, tactile sensors or devices could be found in the robotics and medical industries, or consumer markets.

Around the start of the 1990s, Nicholls and Lee identified that a large market existed for low-cost, robust, accurate and reliable sensors, but saw no significant contribution of tactile sensing technology to real applications in factory systems [16]. Lee even goes so far as to concluded that the technology had been "neglected or even rejected" by industry [4].

Since many advances in computing and robotics technologies were so successful over the previous three decades, this led to very high expectations for tactile sensing technologies. The authors believe that Harmon's predictions were not overly optimistic or unrealistic, especially today, when a wide use of this technology can be seen in smart phones. However, when other technologies were a success and are at a very advanced stage of research today, why has tactile sensor technology failed, at least until the year 2000. There are bitter realities underlying the answer.

4.2. Characterization parameters

Most reported efforts to develop tactile sensors were not supported by rigorous testing; even during laboratory testing, sensor parameters, such as hysteresis, sensitivity, standard deviation and repeatability, which are critical for assessing usefulness of a sensor, are not reported. This has left the technology at a juncture where there are no definitive standards or benchmarks available to guide further development. One attempt to alleviate this situation has been made by Eltaib and Hewit, investigating design considerations for MIS and minimum access surgery [20].

4.3. Cost

The cost of tactile sensors is one of the primary reasons for the failure of the technology to enter industrial and consumer products, especially in the field of health care and service robotics [4]. Lee wrote [4]:

> ... the overriding factor is cost – if large numbers of personal manipulation aids are to be sold, as will be needed to satisfy demand, then costs must be brought down. This is perhaps the most pressing challenge, especially for our engineering and design expertise.

In nearly all reviews of tactile sensor technology, the call for cost effectiveness, repeatability and reliability has been made [16,3,4,2,6,19], yet these issues remain largely ignored. This has led to hesitation in the adoption of the technology, especially in the fields of biomedical engineering and healthcare.

4.4. Poor design criteria

Although Harmon's design criteria are useful and serve as a benchmark by which researchers guide their research, they are too generic. Design requirements for tactile sensing need to be redefined according to the field of application. For example, a biocompatible sensor is not needed for the manufacturing industry and a sensor with wide dynamic range may not be needed in biomedical applications. Likewise, a sensor designed for the biomedical industry with non-biocompatible materials can never get regulatory approval. In short, it seems that task-centered design is necessary.

4.5. Target applications

It is necessary to realize that tactile sensing technology is definitely not the best solution for all robotics applications. Tactile sensors have shown promising results in unstructured environments, but optical, infrared, laser or vision based systems are far superior in structured environments. It is important to realize that tactile-based approaches are an ideal choice in scenarios where vision is partially or totally occluded, or in similar scenarios as those mentioned in Table 6.

Table 6
Proposed application industries with key areas and challenges.

Application industry	Key utility and application areas	Design challenges
Robotics	Dexterous manipulation Tele-robotics Service robots Exploration robots Rescue robots	Arrayed sensors Discrimination and classification algorithms Repeatability, wear resistance and wide dynamic range Customization Characterized response over wide temperature range High frequency response
Biomedical	MIS tools Tele-robotic operations Diagnostics tools Rehabilitation medicine Dentistry Patient care Gait analysis systems	Biocompatibility Rugged to withstand sterilization process Cost due to their disposable nature Characterization and classification algorithms Wireless interfaces Power consumption High frequency response Electrocutaneous feedback mechanisms Safety and reliability Ergonomics
Sports	Posture analysis Sports training	Conformable and customizable sensors Durability Wiring and power constraints Wireless interfaces
Agriculture and food processing	Service robots, such as for fruit picking	Adaptability to unstructured environments Toxin and allergin free construction Hygiene and cleanliness Safe for food handling Dexterous movement Soft grippers Unexplored application area
Aerospace and automobiles industry	Safety studies Safety devices Diagnostic tools Acceleration optimization systems Navigation interfaces for mobile devices	Device centered sensor design Safety and reliability Rugged to withstand high shear, tensile and normal forces Unexplored application area
Consumers products	Healthcare products such as intelligent toothbrushes Service Robots for elderly Textile and clothing	User acceptance Wear resistance and reliability Cost, so that it can target wider application market Rugged to bear abuse

5. Future directions and challenges

5.1. Task centered design criteria

Robotics and biomedical technologies have been attracting increasing levels of attention in recent years. This calls for much sophisticated solutions than before. This can be achieved if task specific design criteria are specified. Task-based design criteria's can help optimize and therefore lower sensor cost.

5.2. Arrayed sensor design and algorithms

In general, single point sensing sensors have reached maturity and their pros and cons are well understood and many promising devices have been reported in literature. Capacitive, resistive, piezoelectric, optical and piezoresistive transduction techniques are well established, but customizable interfaces and characterization/discrimination algorithms are required.

From a hardware design viewpoint, mesh-based, multiple sensing point sensors are required. The distance between the sensing elements is another important criteria. Human glabrous skin can be set as the standard as a starting point, but the desired resolution mainly depends on the requirement of the task to be achieved.

5.3. Gold standard

As emphasized previously, any sensor design parameters should be centered around its application, but in cases where researchers want to explore the area of tactile sensing in general, anatomical structure and characteristics of glabrous skin can be set as the gold standard. Human glabrous skin consists of four types of tactile sensors, also called cutaneous mechanoreceptors. These four types are Pacinian corpuscles, Meissner corpuscles, Merkel discs, and Ruffini corpuscles. The nature and physiology of these receptors has been well established and reported [195–198]. Tactile perception can be understood as the sum of these four receptor functions [195]. A characteristic summary of mechanoreceptors is given in Table 7.

5.4. Frequency response

Previous work has shown that slip has a major frequency component between 10 Hz and 30 Hz [199,34]. Another study has indicated that humans are sensitive to spatial differences at the frequency bands of 1–3 Hz and 18–32 Hz [200]. Pacinian corpuscles, which are sensitive to vibrations, have a bandwidth of approximately 250 Hz and have a lower spatial resolution [201,202]. Hence any sensor with a minimum frequency response of 32 Hz is deemed sufficient to detect incipient slips, which is a desirable endpoint in many robotic and prosthetic applications. Similarly a sensor with a minimum frequency response of 250 Hz is required for the detection of vibration, but can have a lower spatial resolution. A number of PVDF-based sensors have been reported, as discussed earlier in Section 2, but the ability to detect static forces has yet not been achieved, as discussed in Section 2.3.

5.5. Spatial resolution

Early studies to find innervation density of mechanoreceptors in glabrous skin indicated a discrimination threshold of 2–3 mm in

Table 7
Characteristic summary of mechanoreceptors in human glabrous skin.

Type	Merkel	Ruffini	Meissner	Pacini
Number	25%	19%	43%	13%
Adaptivity	Slow	Slow	Fast	Fast
Receptor type	SAI	SAII	FAI	FAII
Field diameter	3–4 mm	>10 mm	3–4 mm	>20 mm
Frequency range	0–30 Hz	0–15 Hz	10–60 Hz	50–1000 Hz
Response to indentation $S(t)$	S, $\frac{ds}{dt}$	S	$\frac{ds}{dt}$	$\frac{d^2s}{dt^2}$
Response to constant indentation	Yes	Yes	No	No
Location	Superficial	Deep	Superficial	Deep
Receptive field	Small	Large	Small	Large
Innervation density	High, variable	Low, constant	High, variable	Low constant
Sensed parameter	Local skin curvature	Directional skin stretch	Skin stretch	Non localized vibration

Table 8
A proposed generic design criteria based on physiological characteristics of mechanoreceptors in the glabrous human skin.

Transduction technique	Capacitive, resistive, piezoelectric, piezoresistive or a combination
Structural design	Arrayed/mesh type. Ease of assembly and disassembly
Spatial resolution	1.25 mm
Frequency response	At least 32 Hz for normal and shear force estimation and 250 Hz for vibration detection
Cost	Low, especially where their use is disposable in nature such as medical devices
Conformability	Not a necessary attribute
Dynamic range	Application specific
Repeatability and stability	High

fingers [203]. Later studies reported a higher spatial resolution of about 1.25 mm [204]. Although some promising mesh type designs are reported [205–209], designs with greater scanning frequency of individual sensing points/elements and greater spatial resolution are required.

5.6. Assembly and maintenance

Ease of assembly and disassembly is also an important area that needs to be addressed. This design criterion is necessary for sensors designed for applications where disposable equipment or parts are required, such as in medical surgery and diagnostic tools. Eltaib and Hewit have attributed it as an important design consideration when designing systems for use in MIS [20].

5.7. Conformity

Conformity is a desirable attribute for specific applications, but not a generic specification for every sensor.

5.8. Cost

Considering MIS where most equipment is disposable, only a suitable sensor with a reasonably low cost would be able to successfully enter the market. Low-cost tactile sensors are required which can sustain wear, have high repeatability and low hysteresis. A proposed design criteria is summarized in Table 8.

6. Conclusion

Developments in tactile sensing and trends over the last four decades have been analyzed. New areas for future applications of tactile sensing technology have been proposed and current challenges have been identified, while emphasizing the importance of application centric design criteria.

6.1. Recent trends

An increase in the demand and uptake of tactile sensing technologies by industry has been observed. This is clearly indicated by the numbers of papers being published and patents being filed. As an indicator, the number of products being patented since 2010 with the US Patent Office, compared to the 1990s, has increased by a factor of ten, as seen in Table 3. Similarly, research activity in this area has also doubled, which is apparent from a comparison with the number of publications in the 1990s, as shown in Table 3.

6.2. Success and maturity

Unlike the previous three decades, where all reviewers have indicated either the rejection or failure of this technology, industrial and commercial enterprises now appear to be on the cusp of accepting this tactile sensing technology. The major uptake has been in mobile devices in the form of tactile touch screens and navigation interfaces. Design engineers seem to take advantage of tactile sensors in order to cope with the requirement for smarter touch interfaces and the ability to navigate through voluminous content with ease. Some of the most successful uses of this technology have been in products like iPods (Apple Inc., USA) and personal digital assistants (PDAs).

6.3. Future of tactile technology

This technology has the potential to aid future advancements in many of the areas discussed earlier. Successful commercial products have provided motivation and possibilities of funding for further research in this technology. Tactile sensing is no longer a laboratory technology. The success of companies such as Pressure Profile Systems Inc. (Los Angeles, USA), Tekscan Inc. (Boston, USA) and X-sensors (Alberta, CANADA) has proven the existence of a market for these products. With more and more gadgets being developed, the need for automation, the acceptance of intelligent robots and biomedical products, the demand for tactile sensing solutions can only be expected to increase.

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References

[1] L. Harmon, Automated tactile sensing, The International Journal of Robotics Research 1 (2) (1982) 3–32.
[2] L. Harmon, Tactile sensing for robots, Robotics and Artificial Intelligence (1984) 109–158.
[3] L. Harmon, Touch-sensing technology – a review, Society of Manufacturing Engineers (1980) 58.

[4] M. Lee, Tactile sensing: new directions, new challenges, The International Journal of Robotics Research 19 (7) (2000) 636.
[5] J. Nevins, D. Whitney, Research on advanced assembly automation, Computer 10 (12) (1977) 24–38.
[6] M. Lee, H. Nicholls, Tactile sensing for mechatronics – a state of the art survey, Mechatronics 9 (1) (1999) 1–31.
[7] S. Omata, Y. Murayama, C. Constantinou, Real time robotic tactile sensor system for the determination of the physical properties of biomaterials, Sensors and Actuators A: Physical 112 (2–3) (2004) 278–285.
[8] P. Puangmali, K. Althoefer, L. Seneviratne, D. Murphy, P. Dasgupta, State-of-the-art in force and tactile sensing for minimally invasive surgery, Sensors Journal, IEEE 8 (4) (2008) 371–381.
[9] M. Ottermo, O. Stavdahl, T. Johansen, Palpation instrument for augmented minimally invasive surgery, in: 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems, 2004 (IROS 2004): Proceedings, vol. 4. IEEE, 2004, pp. 3960–3964.
[10] D. Skoog, D. West, Principles of Instrumental Analysis, vol. 4, Saunders College Publishing, New York, 1985.
[11] B. Jaffe, W. Cook, H. Jaffe, et al., Piezoelectric Ceramics, vol. 1, Academic Press, London, 1971.
[12] A. Okamura, Haptic feedback in robot-assisted minimally invasive surgery, Current Opinion in Urology 19 (1) (2009) 102.
[13] D. Murphy, B. Challacombe, T. Nedas, O. Elhage, K. Althoefer, L. Seneviratne, P. Dasgupta, Equipment and technology in robotics, Archivos Espanoles de Urologia 60 (2007) 349–355.
[14] P. Dario, D. De Rossi, Tactile sensors and the gripping challenge, IEEE Spectrum 22 (8) (1985) 46–52.
[15] K. Pennywitt, Robotic tactile sensing, Byte 11 (1) (1986) 177–200.
[16] H. Nicholls, M. Lee, A survey of robot tactile sensing technology, The International Journal of Robotics Research 8 (3) (1989) 3.
[17] B. Jayawant, Tactile sensing in robotics, Journal of Physics E: Scientific Instruments 22 (1989) 684–692.
[18] R.A. Russell, Robot Tactile Sensing, Prentice-Hall Inc., Upper Saddle River, NJ, USA, 1990.
[19] H. Nicholls, Advanced Tactile Sensing for Robotics, World Scientific Publishing Co. Inc., River Edge, NJ, USA, 1992.
[20] M. Eltaib, J. Hewit, Tactile sensing technology for minimal access surgery – a review, Mechatronics 13 (10) (2003) 1163–1177.
[21] J. Fraden, Handbook of Modern Sensors: Physics, Designs, and Applications, Springer Verlag, 2004.
[22] M. Lee, J. Rowland, Intelligent Assembly Systems, vol. 12, World Scientific Publ. Co. Inc., 1995.
[23] B. Siciliano, O. Khatib, Springer Handbook of Robotics, Springer-Verlag New York Inc., 2008.
[24] P. Regtien, Sensors for Mechatronics, An Elsevier Title, 2012.
[25] S. Beeby, MEMS Mechanical Sensors, Artech House on Demand, 2004.
[26] N. Wettels, Biomimetic Tactile Sensor for Object Identification and Grip Control: A Multi-modal Sensor Mimicking the Human Digit, LAP Lambert Acad. Publ., 2011.
[27] S. Najarian, S. Najjārī yān, J. Dargahi, A. Mehrizi, Artificial Tactile Sensing in Biomedical Engineering, McGraw-Hill Biophotonics, McGraw-Hill, 2009.
[28] D. De Rossi, Artificial tactile sensing and haptic perception, Measurement Science and Technology 2 (1991) 1003–1016.
[29] A. Window, Strain Gauge Technology, Springer, 1992.
[30] R. Dorf, J. Svoboda, Introduction to Electric Circuits, Wiley, 2010.
[31] J. Dargahi, N. Rao, S. Sokhanvar, Design and microfabrication of a hybrid piezoelectric-capacitive tactile sensor, Sensor Review 26 (3) (2006) 186–192.
[32] P. Valdastri, S. Roccella, L. Beccai, E. Cattin, A. Menciassi, M.C. Carrozza, P. Dario, Characterization of a novel hybrid silicon three-axial force sensor, Sensors and Actuators A: Physical 123–124 (2005) 249–257.
[33] J. Jockusch, J. Walter, H. Ritter, A tactile sensor system for a three-fingered robot manipulator, in: IEEE International Conference on Robotics and Automation: Proceedings, vol. 4, 1997, pp. 3080–3086.
[34] J. Son, E. Monteverde, R. Howe, A tactile sensor for localizing transient events in manipulation, in: IEEE International Conference on Robotics and Automation, 1994, pp. 471–476.
[35] R. Howe, A tactile stress rate sensor for perception of fine surface features, Solid-State Sensors and Actuators (1991) 864–867.
[36] S. Yahud, S. Dokos, J. Morley, N. Lovell, Experimental validation of a tactile sensor model for a robotic hand, in: Engineering in Medicine and Biology Society (EMBC) 2009, Proceedings of the Annual International Conference of the IEEE, IEEE, 2009, pp. 2300–2303.
[37] S. Yahud, S. Dokos, J. Morley, N. Lovell, Experimental validation of a polyvinylidene fluoride sensing element in a tactile sensor, in: in: Engineering in Medicine and Biology Society (EMBC), 2010. Proceedings of the Annual International Conference of the IEEE, 2010, pp. 5760–5763.
[38] R. Johansson, G. Loeb, N. Wettels, D. Popovic, V. Santos, Biomimetic tactile sensor for control of grip, US Patent 7,878,075 (2011).
[39] N. Wettels, V. Santos, R. Johansson, G. Loeb, Biomimetic tactile sensor array, Advanced Robotics 22 (8) (2008) 829–849.
[40] D. Hristu, N. Ferrier, R. Brockett, The performance of a deformable-membrane tactile sensor: basic results on geometrically-defined tasks, in: in: Robotics and Automation, 2000. Proceedings, IEEE International Conference on ICRA'00, vol. 1, IEEE, 2000, pp. 508–513.
[41] A. Shashank, M. Tiwana, S. Redmond, N. Lovell, Design, simulation and fabrication of a low cost capacitive tactile shear sensor for a robotic hand, in: in: Annual International Conference of the IEEE Engineering in Medicine and Biology Society, vol. 1, 2009, p. 4132.
[42] H.-K. Lee, J. Chung, S.-I. Chang, E. Yoon, Normal and shear force measurement using a flexible polymer tactile sensor with embedded multiple capacitors, Journal of Microelectromechanical Systems 17 (4) (2008) 934–942.
[43] C. Ko, S. Tseng, M. Lu, A CMOS micromachined capacitive tactile sensor with high-frequency output, Journal of Microelectromechanical Systems 15 (6) (2006) 1708–1714.
[44] T. Salo, T. Vancura, H. Baltes, CMOS-sealed membrane capacitors for medical tactile sensors, Journal of Micromechanics and Microengineering 16 (4) (2006) 769–778.
[45] K. Arshak, D. Morris, O. Korostynska, E. Jafer, A. Arshak, J. Harris, S. Clifford, G. Lyons, Novel Silicone-based Capacitive Pressure Sensors with High Sensitivity for Biomedical Applications, E-Polymers, 2004.
[46] M. Sergio, N. Manaresi, M. Nicolini, D. Gennaretti, M. Tartagni, R. Guerrieri, A textile-based capacitive pressure sensor, Sensor Letters 2 (2) (2004) 153–160.
[47] Y. Shkel, N. Ferrier, Electrostriction enhancement of solid-state capacitance sensing, IEEE/ASME Transactions on Mechatronics 8 (3) (2003) 318–325.
[48] C. Wen, W. Fang, Tuning the sensing range and sensitivity of three axes tactile sensors using the polymer composite membrane, Sensors and Actuators A: Physical 145–146 (1–2) (2008) 14–22.
[49] L. Qin, Q. Li, X.-K. Sun, Research on new tactile sensing costume of intelligent robots, Chinese Journal of Sensors and Actuators 19 (3) (2006) 824–827.
[50] Y. Hasegawa, M. Shikida, T. Shimizu, T. Miyaji, H. Sasaki, K. Sato, K. Itoigawa, Amicromachined active tactile sensor for hardness detection, Sensors and Actuators A: Physical 114 (2–3) (2004) 141–146.
[51] H. Zhang, E. So, Hybrid resistive tactile sensing, IEEE Transactions on Systems Man and Cybernetics, Part B: Cybernetics 32 (1) (2002) 57–65.
[52] M.C. Hsieh, Y.K. Fang, M.S. Ju, G.S. Chen, J.J. Ho, C.H. Yang, P.M. Wu, G.S. Wu, T.Y.F. Chen, A contact-type piezoresistive micro-shear stress sensor for above-knee prosthesis application, Journal of Microelectromechanical Systems 10 (2001) 121–127.
[53] M.C. Hsieh, Y.K. Fang, M.S. Ju, J.J. Ho, S.F. Ting, The development of a new contact type piezoresistive micro-shear-stress sensor, in: in: SPIE – The International Society for Optical Engineering, vol. 4755, 2002, pp. 285–295.
[54] X.-G. Xi, Z.-Z. Luo, Tele-manipulator with tactile tele-presence and myoelectric bionic control, Jiqiren/Robot 31 (3) (2009) 270–275.
[55] M. Qasaimeh, S. Sokhanvar, J. Dargahi, M. Kahrizi, PVDF-based microfabricated tactile sensor for minimally invasive surgery, Journal of Microelectromechanical Systems 18 (1) (2009) 195–207.
[56] C. Li, P.-M. Wu, S. Lee, A. Gorton, M. Schulz, C. Ahn, Flexible dome and bump shape piezoelectric tactile sensors using PVDF–TrFE copolymer, Journal of Microelectromechanical Systems 17 (2) (2008) 334–341.
[57] K. Takashima, S. Horie, T. Mukai, K. Ishida, K. Matsushige, Piezoelectric properties of vinylidene fluoride oligomer for use in medical tactile sensor applications, Sensors and Actuators A: Physical 144 (1) (2008) 90–96.
[58] S. Sokhanvar, M. Packirisamy, J. Dargahi, A multifunctional PVDF-based tactile sensor for minimally invasive surgery, Smart Materials and Structures 16 (4) (2007) 989–998.
[59] Y. Tanaka, M. Tanaka, S. Chonan, Measurement of tactile sensation using sensor system for collecting tactile information, Nihon Kikai Gakkai Ronbunshu, Transactions of the Japan Society of Mechanical Engineers 73 (3) (2007) 817–824.
[60] Y. Tanaka, M. Tanaka, S. Chonan, Development of a sensor system for collecting tactile information, Nihon Kikai Gakkai Ronbunshu, C Hen/Transactions of the Japan Society of Mechanical Engineers Part C 72 (12) (2006) 3818–3825.
[61] S. Motojima, X. Chen, Preparation and characterization of carbon microcoils (CMCs), Bulletin of the Chemical Society of Japan 80 (3) (2007) 449–455.
[62] X. Chen, J. Sakai, S. Yang, S. Motojima, Biomimetic tactile sensors with fingerprint-type surface made of carbon microcoils/polysilicone, Japanese Journal of Applied Physics Part 2: Letters 45 (37–41) (2006) L1019–L1021.
[63] N. Futai, N. Futai, K. Matsumoto, I. Shimoyama, A flexible micromachined planar spiral inductor for use as an artificial tactile mechanoreceptor, Sensors and Actuators A: Physical 111 (2–3) (2004) 293–303.
[64] D. Li, K. Shida, Monostructure touch sensor with multifunction for discrimination of material properties, Electrical Engineering in Japan (English translation of Denki Gakkai Ronbunshi) 117 (3) (1996) 68–75.
[65] S. Takenawa, A soft three-axis tactile sensor based on electromagnetic induction, in: IEEE International Conference on Mechatronics, ICM, 2009.
[66] X. Chen, S. Yang, S. Motojirna, Preparation and property of novel CMC tactile sensors, Nanotechnology Conference and Trade Show (NSTI) (2005) 289–292.
[67] X. Chen, S. Yang, M. Hasegawa, K. Takeuchi, K. Kawabe, S. Motojima, Novel tactile sensors manufactured by carbon microcoils (CMC), in: Proceedings – 2004 International Conference on MEMS, NANO and Smart Systems, ICMENS, 2004, pp. 486–490.
[68] M. Ohka, H. Kobayash, J. Takata, Y. Mitsuya, An experimental optical three-axis tactile sensor featured with hemispherical surface, Nihon Kikai Gakkai Ronbunshu, Transactions of the Japan Society of Mechanical Engineers Part C 74 (6) (2008) 1477–1484.
[69] D.-Z. Tan, Q.-M. Wang, R.-H. Song, X. Yao, Y.-H. Gu, Optical fiber based slide tactile sensor for underwater robots, Journal of Marine Science and Application 7 (2) (2008) 122–126.

[70] M. Ohka, N. Morisawa, H. Suzuki, J. Takata, H. Koboyashi, H. Yussof, A robotic finger equipped with an optical three-axis tactile sensor, in: IEEE International Conference on Robotics and Automation, IEEE, 2008, pp. 3425–3430.
[71] H. Yussof, M. Ohka, H. Kobayashi, J. Takata, M. Yamano, Y. Nasu, Development of an optical three-axis tactile sensor for object handing tasks in humanoid robot navigation system, Studies in Computational Intelligence 76 (2007) 43–51.
[72] M. Ohka, Y. Mitsuya, I. Higashioka, H. Kabeshita, An experimental optical three-axis tactile sensor for micro-robots, Robotica 23 (4) (2005) 457–465.
[73] M. Ohka, Y. Mitsuya, Y. Matsunaga, S. Takeuchi, Sensing characteristics of an optical three-axis tactile sensor under combined loading, Robotica 22 (2) (2004) 213–221.
[74] R. Windecker, S. Franz, H. Tiziani, Optical roughness measurements with fringe projection, Applied Optics 38 (13) (1999) 2837–2842.
[75] K. Kim, K. Lee, W. Kim, K. Park, T. Kim, J. Kim, J. Pak, Polymer-based flexible tactile sensor up to 32 × 32 arrays integrated with interconnection terminals, Sensors and Actuators A: Physical 156 (2) (2009) 284–291.
[76] Y. Zhang, Sensitivity enhancement of a micro-scale biomimetic tactile sensor with epidermal ridges, Journal of Micromechanics and Microengineering 20 (2010) 085012.
[77] Y. Hu, R. Katragadda, H. Tu, Q. Zheng, Y. Li, Y. Xu, Bioinspired 3-D tactile sensor for minimally invasive surgery, Journal of Microelectromechanical Systems 19 (6) (2010) 1400–1408.
[78] S. Hirose, Y. Umetani, The development of soft gripper for the versatile robot hand, Mechanism and Machine Theory 13 (1978) 351–359.
[79] H. Warnecke, R. Schraft, B. Brodbeck, Pilot work site with industrial robots, Water Resources and Environmental Engineering Research Report (State University of New York at Buffalo, Department of Civil Engineering), 1979, pp. 71–86.
[80] G. Stute, H. Erne, Control design of an industrial robot with advanced tactile sensitivity, Water Resources and Environmental Engineering Research Report (State University of New York at Buffalo, Department of Civil Engineering), 1979, pp. 519–527.
[81] J. Dixon, S. Salazar, J. Slagle, Research on tactile sensors for an intelligent naval robot, Water Resources and Environmental Engineering Research Report (State University of New York at Buffalo, Department of Civil Engineering), 1979, pp. 507–517.
[82] R. Abraham, Programmable automation of batch assembly operations, Industrial Robot 4 (3) (1977) 119–131.
[83] E. Pfeiffer, C. Rhode, S. Fabric, An experimental device to provide substitute tactile sensation from the anaesthetic hand, Medical & Biological Engineering 7 (2) (1969) 191–199.
[84] P. Shaw, R. Coleman, W. Beeson, J.B. Mitchell, Design for a microcomputer controlled upper-limb prosthesis, NASA Conference Publication (1979) 21–25.
[85] C.J.Z. Stojiljkovic, Integrated behavior of artifical skin, IEEE Transactions on Biomedical Engineering 24 (4) (1977) 396–399.
[86] I. Kato, Y. Kudo, K. Ichimaru, Artificial softness sensing – an automatic apparatus for measuring viscoelasticity, Mechanism and Machine Theory 12 (1) (1977) 11–26.
[87] G. Kinoshita, S. Aida, M. Mori, A pattern classification by dynamic tactile sense information processing, Pattern Recognition 7 (4) (1975) 243–251.
[88] D. De Rossi, A. Nannini, C. Domenici, Artificial sensing skin mimicking mechanoelectrical conversionproperties of human dermis, IEEE Transactions on Biomedical Engineering 35 (2) (1988) 83–92.
[89] H. Athenstaedt, H. Claussen, D. Schaper, Epidermis of human skin: pyroelectric and piezoelectric sensor layer, Science 216 (4549) (1982) 1018.
[90] J. Sorab, R. Allen, B. Gonik, Tactile sensory monitoring of clinician-applied forces during delivery of newborns, IEEE Transactions on Biomedical Engineering 35 (12) (1988) 1090–1093.
[91] R. Allen, J. Sorab, B. Gonik, Measuring clinician-applied forces during birth using tactile sensing technology, in: in: Engineering in Medicine and Biology Society, 1988. Proceedings of the Annual International Conference of the IEEE, vol. 3, 1988, pp. 1285–1286.
[92] P. Dario, D. De Rossi, C. Domenici, R. Francesconi, Ferroelectric polymer tactile sensors with anthropomorphic features, in: in: 1984 IEEE International Conference on Robotics and Automation: Proceedings, vol. 1, 1984, pp. 332–340.
[93] D. Burger, C. Liard, G. Roux, Compact electronic module for the non-visual display of alphanumerical data, in: Engineering in Medicine and Biology Society Annual Conference, 1987, pp. 1731–1732.
[94] C. Liard, D. Burger, G. Roux, Portable terminal for the blind based on an audio-tactile display, in: Engineering in Medicine and Biology Society Annual Conference, 1987, pp. 1956–1957.
[95] M. Neuman, Physical and chemical sensors for medical instrumentation, Medical Progress through Technology 9 (2–3) (1982) 95.
[96] M. Raibert, J. Tanner, Design and implementation of a VLSI tactile sensing computer, The International Journal of Robotics Research 1 (3) (1982) 3.
[97] P. Dario, Tactile sensing: technology and applications, Sensors Actuators (1) (1991) 251–256.
[98] J.E. Wickham, The new surgery, British Medical Journal 29 (1987) 1581–1582.
[99] G. Litynski, Endoscopic surgery: the history the pioneers, World Journal of Surgery 23 (8) (1999) 745–753.
[100] U. Voges, Technology in laparoscopy – what to expect in the future, Urologe Ausgabe (a) 35 (1996) 208–214.
[101] S. Sastry, M. Cohn, F. Tendick, Milli-robotics for remote minimally invasive surgery, Robotics and Autonomous Systems 21 (3) (1997) 305–316.
[102] D. Pawluk, J. Son, P. Wellman, W. Peine, R. Howe, A distributed pressure sensor for biomechanical measurements, Journal of Biomechanical Engineering 120 (2) (1998) 302–305.
[103] P. Brett, R. Stone, A technique for measuring contact force distribution in minimally invasive surgical procedures, Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine 211 (4) (1997) 309–316.
[104] S. Matsumoto, R. Ooshima, K. Kobayashi, N. Kawabe, T. Shiraishi, Y. Mizuno, H. Suzuki, S. Umemoto, A tactile sensor for laparoscopic cholecystectomy, Surgical Endoscopy 11 (9) (1997) 939–941.
[105] S. Barnes, D. Morr, E. Oggero, G. Pagnacco, N. Berme, The realization of a haptic (force feedback) interface device for the purpose of angioplasty surgery simulation, Biomedical Sciences Instrumentation 33 (1997) 19–24.
[106] P. Plinkert, I. Baumann, E. Flemming, A tactile sensor for differentiation of tissue in minimally invasive ENT surgery [ein taktiler sensor zur gewebe-differenzierung in der minimal invasiven hno-chirurgie], Laryngo-Rhino-Otologie 76 (9) (1997) 543–549.
[107] L. Kory, A. Morimoto, T. McFarlane, T. Bocklage, M. Curet, Force sensor for laparoscopic surgical instrument, Journal of Investigative Medicine 47 (2) (1999).
[108] H. Fischer, R. Trapp, Tactile optical sensor for use in minimal invasive surgery, Studies in Health Technology and Informatics 29 (1996) 623–629.
[109] T. Ohtsuka, A. Furuse, T. Kohno, J. Nakajima, K. Yagyu, S. Omata, Application of a new tactile sensor to thoracoscopic surgery: experimental and clinical study, The Annals of Thoracic Surgery 60 (3) (1995) 610–613.
[110] Service Robot, MCB University Press, Bradford, West Yorkshire, England, 1995.
[111] K. Hohm, E. Brucherseifer, H. Boetselaars, Using incremental learning for transition from rule based behavior to motion sequences for motor control of a flexible robot system, in: in: Proceedings of the IEEE International Conference on Systems, Man and Cybernetics vol. 6, 1999, pp. VI655–VI660.
[112] M. Seitz, Towards autonomous robotic servicing: using an integrated hand-arm-eye system for manipulating unknown objects, Robotics and Autonomous Systems 26 (1) (1999) 23–42.
[113] H. Ueno, Y. Saito, Model-based vision and intelligent task scheduling for autonomous human-type robot arm, Robotics and Autonomous Systems 18 (1–2) (1996) 195–206.
[114] B. Yoshimi, P. Allen, Visual control of grasping, the confluence of vision and control, Springer, 1998, 195–209.
[115] P. Puangmali, K. Althoefer, L. Seneviratne, D. Murphy, P. Dasgupta, State-of-the-art in force and tactile sensing for minimally invasive surgery, IEEE Sensors Journal 8 (4) (2008) 371–380.
[116] O. Bholat, R. Haluck, W. Murray, P. Gorman, T. Krummel, Tactile feedback is present during minimally invasive surgery, Journal of the American College of Surgeons 189 (4) (1999) 349–355.
[117] J. Shah, D. Buckley, J. Frisby, A. Darzi, Depth cue reliance in surgeons and medical students, Surgical Endoscopy 17 (9) (2003) 1472–1474.
[118] P. Schauer, S. Ikramuddin, G. Hamad, W. Gourash, The learning curve for laparoscopic roux-en-y gastric bypass is 100 cases, Surgical Endoscopy 17 (2) (2003) 212–215.
[119] G.C. Burdea, Force and Touch Feedback for Virtual Reality, John Wiley & Sons Inc., New York, NY, USA, 1996.
[120] D. Camarillo, T. Krummel, J. Salisbury, Robotic technology in surgery: past present and future, The American Journal of Surgery 188 (4S1) (2004) 2–15.
[121] B. Bethea, A. Okamura, M. Kitagawa, T. Fitton, S. Cattaneo, V. Gott, W. Baumgartner, D. Yuh, Application of haptic feedback to robotic surgery, Journal of Laparoendoscopic & Advanced Surgical Techniques 14 (3) (2004) 191–195.
[122] M. Tavakoli, R. Patel, M. Moallem, A force reflective master–slave system for minimally invasive surgery, in: in: IEEE International Conference on Intelligent Robots and Systems, vol. 4, 2003, pp. 3077–3082.
[123] A. Okamura, R. Webster, J. Nolin, K. Johnson, H. Jafry, The haptic scissors: cutting in virtual environments, in: IEEE International Conference on Robotics and Automation, vol. 1, IEEE; 1999, 2003, pp. 828–833.
[124] T. Hu, A. Castellanos, G. Tholey, J. Desai, Real-time haptic feedback in laparoscopic tools for use in gastro-intestinal surgery, Lecture Notes in Computer Science (2002) 66–74.
[125] J. Dargahi, S. Najarian, An integrated force-position tactile sensor for improving diagnostic and therapeutic endoscopic surgery, Biomedical Materials and Engineering 14 (2) (2004) 151–166.
[126] J. Dargahi, S. Najarian, K. Najarian, Development and three-dimensional modelling of a biological-tissue grasper tool equipped with a tactile sensor, Canadian Journal of Electrical and Computer Engineering 30 (4) (2005) 225–230.
[127] J. Peirs, J. Clijnen, D. Reynaerts, H. Brussel, P. Herijgers, B. Corteville, S. Boone, A micro optical force sensor for force feedback during minimally invasive robotic surgery, Sensors and Actuators A: Physical 115 (2–3) (2004) 447–455.
[128] K. Shimoga, A survey of perceptual feedback issues in dexteroustelemanipulation. II. Finger touch feedback, in: IEEE Virtual Reality Annual International Symposium, 1993, pp. 271–279.
[129] C. Wagner, N. Stylopoulos, R. Howe, The role of force feedback in surgery: analysis of blunt dissection, in: 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2002, pp. 68–74.
[130] G. Burdea, Force and Touch Feedback for Virtual Reality, John Wiley & Sons Inc., New York, NY, USA, 1996.

[131] G. Tholey, J. Desai, A. Castellanos, Force feedback plays a significant role in minimally invasive surgery, Annals of Surgery 241 (1) (2005) 102–109.
[132] C.-H. King, M. Culjat, M. Franco, C. Lewis, G.W.B.J.E.P. Dutson, Tactile feedback induces reduced grasping force in robot-assisted surgery, IEEE Transactions on Haptics 2 (2) (2009) 103–110.
[133] M. Culjat, C. King, M. Franco, J. Bisley, W. Grundfest, E. Dutson, Pneumatic balloon actuators for tactile feedback in robotic surgery, Industrial Robot: An International Journal 35 (5) (2008) 449–455.
[134] C. King, A. Higa, M. Culjat, S. Han, J. Bisley, G. Carman, E. Dutson, W. Grundfest, A pneumatic haptic feedback actuator array for robotic surgery or simulation, Studies in Health Technology and Informatics 125 (2006) 217.
[135] R. Hobson, S. Wilson, F. Veith, Vascular Surgery: Principles and Practice, Marcel Dekker, 2004.
[136] W. Peine, Remote palpation instruments for minimally invasive surgery, PhD thesis, Division of Engineering and Applied Sciences, Harvard University, 1999.
[137] S. Berman, Vascular Access in Clinical Practice, Informa HealthCare, 2002.
[138] H. Akbari, Y. Kosugi, K. Kihara, A novel method for artery detection in laparoscopic surgery, Surgical Endoscopy 22 (7) (2008) 1672–1677.
[139] A. Mehrizi, S. Najarian, M. Moini, J. Dargahi, R. Ahmadi, A novel method in exploration of arteries inside a tissue and assessment of the arteries by computational approach, in: in: IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM), IEEE, 2010, pp. 932–936.
[140] A. Mehrizi, S. Najarian, R. Khodambashi, S. Dehkhoda, A novel method of tactile assessment of arteries using computational approach, International Journal of Academic Research 3 (2011) 1059–1064.
[141] M. Mack, Minimally invasive and robotic surgery, Journal of the American Medical Association 285 (5) (2001) 568.
[142] A. Novick, I. Gill, Operative Urology at the Cleveland Clinic, vol. 1, Humana Press Inc., 2006.
[143] E. Afshari, S. Najarian, Modeling and analysis of the effects of nephrolithiasis in kidney using a computational tactile sensing approach, Proceeding of World Academy of Science, Tokyo, Japan: Engineering and Technology (ICMS) 41 (2009) 378–381.
[144] E. Afshari, S. Najarian, N. Simforoosh, S. Farkoush, Evaluation of a new method for detection of kidney stone during laparoscopy using 3D conceptual modeling, International Journal of Medicine and Medical Sciences 1 (2010) 56–61.
[145] E. Afshari, S. Najarian, N. Simforoosh, Application of artificial tactile sensing approach in kidney-stone-removal laparoscopy, Bio-Medical Materials and Engineering 20 (5) (2010) 261–267.
[146] I. Barman, S. Guha, Analysis of a new combined stretch and pressure sensor for internal nodule palpation, Sensors & Actuators A: Physical 125 (2) (2006) 210–216.
[147] T. Hall, Y. Zhu, C. Spalding, In vivo real-time freehand palpation imaging, Ultrasound in Medicine & Biology 29 (3) (2003) 427–435.
[148] J. Lee, C. Won, K. Yan, Y. Yu, L. Liao, Tactile sensation imaging for artificial palpation, Haptics: Generating and Perceiving Tangible Sensations (2010) 373–378.
[149] M. Ayyildiz, B. Guclu, M. Yildiz, C. Basdogan, A novel tactile sensor for detecting lumps in breast tissue, Haptics: Generating and Perceiving Tangible Sensations (2010) 367–372.
[150] S. Schostek, M. Binser, F. Rieber, C. Ho, M. Schurr, G. Buess, Artificial tactile feedback can significantly improve tissue examination through remote palpation, Surgical Endoscopy 24 (9) (2010) 2299–2307.
[151] H. Roham, S. Najarian, S. Hosseini, J. Dargahi, Design and fabrication of a new tactile probe for measuring the modulus of elasticity of soft tissues, Sensor Review 27 (4) (2007) 317–323.
[152] N. Narayanan, A. Bonakdar, J. Dargahi, M. Packirisamy, R. Bhat, Design and analysis of a micromachined piezoelectric sensor for measuring the viscoelastic properties of tissues in minimally invasive surgery, Smart Materials and Structures 15 (2006) 1684.
[153] M. Helve, Imaging analysys: mammography, in: in: Diseases of the Breast, 3rd ed., Wolters Kluwer Company, Philadelphia, 2004, pp. 131–148.
[154] T. Bevers, Breast cancer screening and diagnosis guidelines. national comprehensive cancer network, Clinical Practice Guidelines in Oncology 1 (2006) 1–38.
[155] R. Laxminarayan, J. Chow, S.A. Shahid-Salles, Intervention cost-effectiveness: overview of main messages, Disease control priorities in developing countries (2006) 35–86.
[156] A. Sarvazyan, V. Egorov, J. Son, C. Kaufman, Cost-effective screening for breast cancer worldwide: current state and future directions, Breast Cancer 1 (2008) 91.
[157] Medical Tactile Inc., suretouch product overview, http://www.suretouch.com.au/overview.htm.
[158] C. Kaufman, L. Jacobson, B. Bachman, L. Kaufman, Digital documentation of the physical examination: moving the clinical breast exam to the electronic medical record, The American Journal of Surgery 192 (4) (2006) 444–449.
[159] V. Semiglazov, A. Manikhas, V. Moiseenko, S. Protsenko, R. Kharikova, I. Seleznev, R. Popova, N. Migmanova, A. Orlov, N. Barash, Results of a prospective randomized investigation to evaluate the significance of self-examination for the early detection of breast cancer, Voprosy Onkologii 49 (4) (2003) 434–441.
[160] K. Ohnuki, S. Kuriyama, N. Shoji, Y. Nishino, I. Tsuji, N. Ohuchi, Cost-effectiveness analysis of screening modalities for breast cancer in Japan with special reference to women aged 40–49 years, Cancer Science 97 (11) (2006) 1242.
[161] A. Tosteson, N. Stout, D. Fryback, S. Acharyya, B. Herman, L. Hannah, E. Pisano, Cost-effectiveness of digital mammography breast cancer screening, Annals of Internal Medicine 148 (1) (2008) 1.
[162] D. Saslow, C. Boetes, W. Burke, S. Harms, M. Leach, C. Lehman, E. Morris, E. Pisano, M. Schnall, S. Sener, et al., American cancer society guidelines for breast screening with MRI as an adjunct to mammography, CA: A Cancer Journal for Clinicians 57 (2) (2007) 75.
[163] J. Groenewoud, R. Pijnappel, M. van den Akker-Van Marle, E. Birnie, T. Buijs-van der Woude, W. Mali, H. de Koning, E. Buskens, Cost-effectiveness of stereotactic large-core needle biopsy for nonpalpable breast lesions compared to open-breast biopsy, British Journal of Cancer 90 (2) (2004) 383.
[164] B. Hillner, J. Hayman, Cost and Cost-effectiveness Considerations, Diseases of the Breast, 3rd ed., Lippincott Williams & Wilkins, Philadelphia, PA, 2004, pp. 1497–1513.
[165] R. DeMeis, Piezos step up gait analysis: treadmill force plates measure real-world patient mobility, Design News 53 (1998) 98–102.
[166] K. Postema, H. Hermens, J. De Vries, H. Koopman, W. Eisma, Energy storage and release of prosthetic feet. Part 1. Biomechanical analysis related to user benefits, Prosthetics and Orthotics International 21 (1) (1997) 17–27.
[167] M. Elliott, X. Ma, P. Brett, A smart sensing platform for the classification of ambulatory patterns, Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine 223 (5) (2009) 567–575.
[168] A.M. Mazid, A.B.M.S. Ali, Opto-tactile sensor for surface texture pattern identification using support vector machine, 10th International Conference on Control, Automation, Robotics and Vision, ICARCV 2008 (2008) 1830–1835.
[169] S. Kim, J. Engel, C. Liu, D. Jones, Texture classification using a polymer-based mems tactile sensor, Journal of Micromechanics and Microengineering 15 (5) (2005) 912–920.
[170] S. Baglio, G. Muscato, N. Savalli, Tactile measuring systems for the recognition of unknown surfaces, IEEE Transactions on Instrumentation and Measurement 51 (3) (2002) 522–531.
[171] A. Mazid, R. Russell, A robotic opto-tactile sensor for assessing object surface texture, in: in: 2006 IEEE Conference on Robotics, Automation and Mechatronics, IEEE, 2006, pp. 1–5.
[172] J. Edwards, J. Lawry, J. Rossiter, C. Melhuish, Extracting textural features from tactile sensors, Bioinspiration & Biomimetics 3 (2008) 035002.
[173] G. Hellard, R. Russell, A robust sensitive and economical tactile sensor for a robotic manipulator, in: in: Proceedings of the 2002 Australasian Conference on Robotics and Automation, Auckland, Citeseer, 2002, pp. 27–29.
[174] J. Sanders, C. Daly, Normal and shear stresses on a residual limb in a prosthetic socket during ambulation: comparison of finite element results with experimental measurements, Journal of Rehabilitation Research and Development 30 (1993), 191–191.
[175] G. Reiber, Who is at risk of limb loss and what to do about it? Development 31 (4) (1994) 357–362.
[176] K. Gallagher, Z. Liu, M. Xiao, H. Chen, L. Goldstein, D. Buerk, A. Nedeau, S. Tho, O. Velazquez, Diabetic impairments in no-mediated endothelial progenitor cell mobilization and homing are reversed by hyperoxia and sdf-1alpha, Journal of Clinical Investigation 117 (5) (2007) 1249.
[177] T. Fahey III, A. Sadaty, W. Jones II, A. Barber, B. Smoller, G. Shires, Diabetes impairs the late inflammatory response to wound healing, Journal of Surgical Research 50 (4) (1991) 308–313.
[178] D. Greenhalgh, al. et, Wound healing and diabetes mellitus, Clinics in Plastic Surgery 30 (1) (2003) 37.
[179] L. Beccai, S. Roccella, A. Arena, F. Valvo, P. Valdastri, A. Menciassi, M. Carrozza, P. Dario, Design and fabrication of a hybrid silicon three-axial force sensor for biomechanical applications, Sensors & Actuators A: Physical 120 (2) (2005) 370–382.
[180] P. Valdastri, S. Roccella, L. Beccai, E. Cattin, A. Menciassi, M. Carrozza, P. Dario, Characterization of a novel hybrid silicon three-axial force sensor, Sensors & Actuators A: Physical 123 (2005) 249–257.
[181] L. Beccai, S. Roccella, A. Arena, A. Menciassi, Silicon-based three axial force sensor for prosthetic applications, in: Proceedings of the 7th Italian Conference: Sensors and Microsystems: Bologna, Italy, 4–6 February, World Scientific, 2002, p. 250.
[182] E. Bosman, B. Van Hoe, J. Missinne, G. Van Steenberge, S. Kalathimekkad, P. Van Daele, Unobtrusive packaging of optoelectronic devices for optical tactile and shear sensors, in: 2011 Fifth International Conference on Sensing Technology (ICST), IEEE, 2011, pp. 504–509.
[183] B. Petzold, M. Zaeh, B. Faerber, B. Deml, H. Egermeier, J. Schilp, S. Clarke, A study on visual auditory and haptic feedback for assembly tasks, Presence: Teleoperators & Virtual Environments 13 (1) (2004) 16–21.
[184] C. Shing, C. Fung, T. Chuang, I. Penn, J. Doong, The study of auditory and haptic signals in a virtual reality-based hand rehabilitation system, Robotica 21 (02) (2003) 211–218.
[185] K. Kaczmarek, J. Webster, Electrotactile and vibrotactile displays for sensory substitution systems, IEEE Transactions on Biomedical Engineering 38 (1991) 1–16.
[186] J. Sabolich, G. Ortega, G. Schwabe IV, System and method for providing a sense of feel in a prosthetic or sensory impaired limb, US Patent 6,500,210 (2002).
[187] J. Missinne, E. Bosman, B. Van Hoe, G. Van Steenberge, S. Kalathimekkad, P. Van Daele, J. Vanfleteren, Flexible shear sensor based on embedded optoelectronic components, Photonics Technology Letters, IEEE 23 (12) (2011) 771–773.
[188] J. Missinne, E. Bosman, B. Van Hoe, R. Verplancke, G. Van Steenberge, S. Kalathimekkad, P. Van Daele, J. Vanfleteren, Ultra thin optical tactile shear sensor, Procedia Engineering 25 (2011) 1393–1396.

[189] C. Antfolk, C. Balkenius, G. Lundborg, B. Rosén, F. Sebelius, A tactile display system for hand prostheses to discriminate pressure and individual finger localization, Journal of Medical and Biological Engineering 30 (6) (2010) 355–359.
[190] Z. Jiang, S. Arabshahi, T. Watanabe, A study on design concept for a braille tactile sensor segment using softness parameters, JSME International Journal Series C: Mechanical Systems Machine Elements and Manufacturing 49 (2) (2006) 480–487.
[191] K. Miyata, M. Tanaka, T. Nishizawa, S. Chonan, Wearable tactile sensor system for reading braille, International Journal of Applied Electromagnetics and Mechanics 23 (3–4) (2006) 203–215.
[192] S. Arabshahi, Z. Jiang, Development of a tactile sensor for braille pattern recognition: sensor design and simulation, Smart Materials and Structures 14 (6) (2005) 1569–1578.
[193] M. Tanaka, K. Miyata, T. Nishizawa, S. Chonan, Development of a tactile sensor system for reading braille: fundamental characteristics of the prototype sensor system, Smart Materials and Structures 14 (4) (2005) 483–487.
[194] A. Haber-Olguin, J. Quintero-Lopez, Braille code electronic simulator device with interactive multimedia interface, Revista Mexicana de Oftalmologia 79 (1) (2005) 32–36.
[195] K. Johnson, The roles and functions of cutaneous mechanoreceptors, Current Opinion in Neurobiology 11 (4) (2001) 455–461.
[196] D. Silverthorn, Human Physiology: an Integrated Approach, Benjamin-Cummings Publishing Company, 2004.
[197] L. Sherwood, Human Physiology: From Cells to Systems, Thomson Brooks/Cole, 2000.
[198] J. Hall, Pocket Companion to Guyton & Hall Textbook of Medical Physiology, Elsevier Saunders, 2006.
[199] R. Howe, M. Cutkosky, Sensing skin acceleration for slip and texture perception, in: in: IEEE International Conference on Robotics and Automation: Proceedings, 1989, pp. 145–150.
[200] K.-U. Kyung, M. Ahn, D.-S. Kwon, M. Srinivasan, Perceptual and biomechanical frequency response of human skin: implication for design of tactile displays, in: Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2005, pp. 96–101.
[201] S. Bolanowski Jr., G. Gescheider, R. Verrillo, C. Checkosky, Four channels mediate the mechanical aspects of touch, The Journal of the Acoustical society of America 84 (1988) 1680.
[202] R. Johansson, A. Vallbo, Tactile sensibility in the human hand: relative and absolute densities of four types of mechanoreceptive units in glabrous skin, The Journal of Physiology 286 (1) (1979) 283–300.
[203] R. Verrillo, A duplex mechanism of mechanoreception, in: The Skin Senses: Proceedings, Thomas, 1968, p. 139.
[204] J. Craig, K. Lyle, A comparison of tactile spatial sensitivity on the palm and fingerpad, Perception and Psychophysics 63 (2) (2001) 337–347.
[205] T. Papakostas, J. Lima, M. Lowe, T. Inc, M. Boston, A large area force sensor for smart skin applications, in: Proceedings of IEEE Sensors, vol. 2, 2002.
[206] K. Choi, S. Jiang, Z. Li, Multingered robotic hands: contact experiments using tactile sensors, in: Proceedings of IEEE International Conference on Robotics & Automation, 1998, pp. 2268–2273.
[207] R.A. Boie, G.L. Miller, Conformable tactile sensor, US Patent No. 4526043 (July 2, 1985).
[208] R. Dahiya, M. Valle, G. Metta, L. Lorenzelli, C. Collini, Tactile sensing arrays for humanoid robots, in: Proceedings of the 2007 PhD Research in Microelectronics and Electronics Conference, PRIME, 2007, pp. 201–204.
[209] R. Dahiya, G. Metta, M. Valle, Development of fingertip tactile sensing chips for humanoid robots, in: IEEE International Conference on Mechatronics, ICM, 2009, pp. 1–6.

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