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# Sensitivity analysis of a novel tactile probe for measurement of tissue softness with applications in biomedical robotics

Javad Dargahi [a,1], Siamak Najarian [b,*], Bin Liu [a]

[a] CONCAVE Research Centre, CR-200, Concordia University, Department of Mechanical and Industrial Engineering, 1455 de Maisonneuve Blvd. West, Montreal, Quebec, Canada H3G 1M8

[b] Center of Excellence of Biomedical Engineering, Biomechanics Department, Faculty of Biomedical Engineering, Amirkabir University of Technology, Tehran 15875-4413, Iran

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**Abstract**

In this research paper, the sensitivity of a novel tactile probe is investigated both experimentally and theoretically which has applications in robotic surgery. Using this probe, it is possible to determine the softness of objects that come into contact with it. As the sensing elements, two piezoelectric films of PVDF are incorporated into the probe and the combination of the resulting output voltages is related to the object softness. The probe consists of three distinct parts. The base of the probe, which serves as the rigid support for the whole sensor, is made of a rigid Plexiglas. The remaining parts are constructed from two different compressible materials with a wide range of compressibility. Our experiments show that, depending on the softness of the sensed objects, there is a distinct difference between the output voltages. Harder objects tend to manifest waveforms with higher peaks and with steeper rises at the start of the tests. These important features were used and a number of tests were conducted in order to analyze the sensitivity of the designed probe. A mathematical model based on the properties of various elements in the tactile probe is developed, which could reasonably predict the general performance of the system. The effects of different parameters such as, softness of the two compressible sections of the probe, their thickness, and their corresponding area ratios are tested experimentally. Using the developed model, the experimental results are predicted with good accuracy and the discrepancy is found to be within the accepted range. This prototype has applications in determining the softness of biological tissues/objects both in routine clinical examinations and during surgeries.


*Keywords:* Softness measurements; Sensitivity analysis; Deformable objects; Tactile probe

## 1. Introduction

Tactile sensing is of great importance in different types of surgeries [1]. This includes detecting the presence or absence of a grasped tissue/object or even mapping a complete tactile image [2–5]. Force signature can give us a great deal of information about the state of gripping or manipulation of an object or biological tissue [6]. In medical applications, a force sensitivity within the range of 0.1–11 N is generally considered satisfactory [7]. In different biomedical engineering and medical robotics applications, tactile sensors can be used to sense a wide range of stimuli. Normally, in order to improve the efficiency of these types of sensors, an array of sensors is utilized [8,9]. Increasing the number of sensors may even provide the operators with the capability of measuring a number of tactile properties.

In [10], a tactile sensor with standing piezoresistive cantilevers embedded in an elastic material is proposed. The sensor detects the shear stress applied on its surface. Each standing piezoresistive cantilever in the elastic material detects a certain axial component of applied shear stress. By arranging this standing piezoresistive cantilever in orthogonal directions, the directions and the magnitudes of applied shear stress is detected. In [11], the concept of an inexpensive PVDF pyroelectric radiation sensor of large aperture is described and the design details of the pyroelectric sensor based on the PVDF polymer are given. A micro-mechanical sensing platform is described in [12] with which the various elastic properties of the ovum can be characterized using uniaxial measurements. In [13], novel textiles are developed using conducting polymer coatings which are deposited on a foam substrate. The foam they used is a soft,

* Corresponding author.
*E-mail addresses:* jdargahi@alcor.concordia.ca (J. Dargahi), najarian@aut.ac.ir (S. Najarian).
[1] Tel.: +1 514 848 7967; fax: +1 514 848 8635.

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porous conductive solid made by chemically oxidizing pyrrole in the presence of a polyurethane foam. The resulting structure is sensitive to pressure exerted from all three dimensions making it attractive for use as wearable sensors for medical applications.

An important application of tactile sensing is in surgeries including minimally invasive surgery (MIS). During MIS procedures, any inhibitions on the surgeon's sensory abilities might lead to undesirable results [14]. This type of surgery has many advantages including reducing trauma, alleviating pain, requiring smaller incisions, faster recovery time, and reducing post-operation complications [15]. However, it suffers from a decrease in the tactile sensory perception of the surgeon. To improve the results of these surgeries, it would be advantageous for the surgeon to have an idea about the softness of the tissue in contact with the tools. This would lead to much safer handling of the tissues, while performing different maneuvers on the organs. For instance, in order to improve the manipulation ability of endoscope, a new tactile sensor system using image processing has been developed [16]. As this system uses an infrared (IR) cut pattern, it is possible to install the sensor in the tip of an existing endoscope easily. In a research work, using a modified commercial endoscopic tool, the magnitude of the applied force was measured by strain gauges, and then the position of the grasper was determined with an optical detector [17]. They obtained force–displacement data and identified objects with five different elastic properties. A report has been published on compliance of a hard rubber embedded in a block of foam using remote palpation [1]. Additionally, an endoscopic and robotic micro-machined sensor has been designed and fabricated using PVDF film [5]. Design, fabrication, and theoretical studies of a micro-machined piezoelectric tactile sensor for an endoscopic grasper have been discussed [18]. The sensor exhibited high force sensitivity, high dynamic range, good linearity, and high signal to noise ratio. In another work, a force–moment sensor has been placed into the distal shaft of a laparoscopic forceps as well as a tactile sensor array between the jaws of the forceps [19]. The piezoresistive sensor array used was a foil sensor with 64 measuring points. Various attempts have been made to tackle the problem of reducing the number of sensors using PVDF films [20–22].

Another application of a probe, which is capable of measuring the softness of tissues based on its tactile features, is in detecting various tumors in human body [23]. There are different ways for detecting breast cancer which is one of the most common forms of cancers in women. This disease can be detected either manually, e.g., by clinical breast examination (CBE) or by using medical imaging methods such as mammography or sonography [24]. By increasing its size, a cancerous tumor can exhibit various symptoms such as change in size or shape of the breast (i.e., a change in its tactile properties). The development of an active haptic sensor for monitoring skin conditions has been discussed [25]. The base of the tactile sensor is an aluminum cylinder, around which a polyurethane rubber, a PVDF film, a protective surface layer of an acetate film and lace are stacked in sequence. Their experimental results show that the sensor system works well as a haptic sensor for monitoring skin conditions. A research has been published that discusses the preliminary tests and basic design parameters for single tactels using electrorheological fluids [26]. The final aim was to produce a prototype three-dimensional tactile display comprising electrically switchable micro-machined cells whose mechanical moduli are governed by phase changes experienced by electrorheological fluids. A micro-tactile sensor has been developed to measure elasticity together with the instant of contact [27]. Using finite element modeling, they found a frequency where longitudinal and rotational vibration modes exist and used these results to signal touch detection.

Following the above-mentioned progress, the sensitivity analysis of a novel softness measurement probe is presented in this research work. The designed probe can be safely employed in determining the softness of various objects or biological tissues. This prototype has the potential of being miniaturized and be used in artificial palpation procedures.

## 2. Materials and methods

### 2.1. Tactile probe design

A tactile probe was constructed which consisted of three major parts. The base of the probe was made of a rigid Plexiglas while for the central part and the peripheral part of the probe, various materials with a wide range of softness were used. Both the central and the peripheral parts of the probe were compressible. The reason for selecting compressible materials for this probe is mainly related to its application [28,29]. That is to say, due to its contact with biological tissues, having very hard materials in the probe will induce some uncomfortable pressures on the human skin. A schematic representation of the designed probe is shown in Fig. 1.

Two PVDF films (i.e., PVDF1 and PVDF2) were placed between the top sections and the bottom base of the probe and made up the sensor part of the whole assembly. The same structure can be used as the sensing part of a robotic finger [30–32]. The inclusion scheme of the sensing part in a typical robotic finger, represented as a cylindrical object, is also shown in the right hand side of the same figure.

A sensor was constructed using the schematic presented above. A photograph of the sensed object together with the sensor is shown in Fig. 2. Here, a foam-like material is placed on top of the sensor and the softness of this sensed object can be measured experimentally. For the sensor part of the probe, a 110 $\mu$m metalized and uni-axially poled PVDF film (Good Fellow Company, USA) was put between the upper cubical parts and the lower Plexiglas base [33]. One of the films (PVDF1) was located right below the compressible cube 2 and the other one (PVDF2) beneath the compressible cube 3. A 2 mm $\times$ 1 mm channel groove was cut on the bottom side of the peripheral cube in order to isolate the output

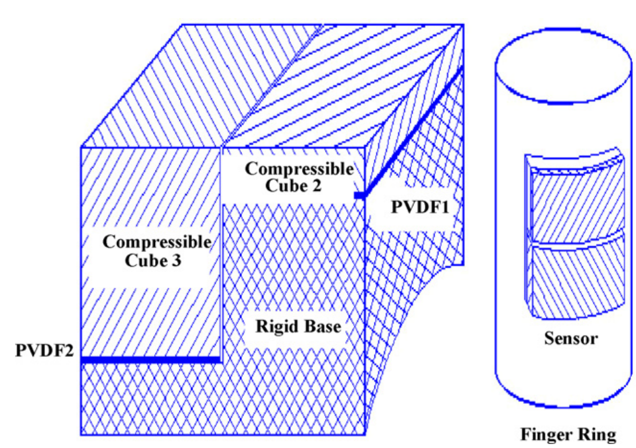


Fig. 1. Schematic of the designed probe with its major constituting parts.