Pneumatic-based methods for force sensing and contact detection in telemanipulation tasks

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to Erica,
to those who believe in theirselves

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Most importantly, none of this would have been possible without the patience and the love of Andrea, who has inexplicably forgiven me for all the time I took away from him. Research is time demanding, they say.

Abstract

Teleoperation frameworks require a rich flow of information from the slave to the master side to be effective. While visual information is usually provided in any master-slave system, haptic perception is often missing. Despite the importance of the sense of touch while performing surgical procedures, minimally invasive robotic surgery still lacks the reproduction of haptic stimuli at the master side, mostly due to the difficulties in measuring forces at the contact site. However, there could be also procedures in open surgery in which a reduction of the natural haptic perception may occur, for example because vibrations generated by the surgical tool affect the surgeon's perception.

This thesis addresses the challenge of measuring forces between surgical instruments and patient's tissues both in robotic and open surgery, presenting innovative pneumatic force sensors that rely on pressure variations inside one or more chambers. Performance comparisons with accurate commercial force sensors proved the feasibility and effectiveness of the proposed approaches. Besides, many advantages can be appreciated in terms of size, cost, biocompatibility, possibility of changing sensor features such as stiffness according to the application, and absence of electronic components into the patient's body.

The achieved results paved the way towards the exploitation of novel pneumatic-based devices for contact detection in more general robotic manipulation scenarios. In this context, a pneumatic device has been proposed to create soft inclusions in the environment that can be used by rigid grippers to achieve safer grasps. The use of soft sensing modules allows us to detect the contact between the gripper and the environment during grasp approach, and to estimate the approximate location and weight distribution of the object to be grasped. A system that combines the precision of rigid grippers with the adaptability of pneumatic-based devices was developed and successfully tested in grasping tasks with several different objects, taking advantage of the strengths of both rigid and soft robotics approaches.

Contents

Chapter 1

Introduction

> To touch can be to give life.
>
> Michelangelo

1.1 The sense of touch

Touch is the most distributed sense in the human body and it is truly fundamental to human communication, bonding, and health [1]. It has been described as the most fundamental means of contact with the world [2] and the simplest and most straightforward of all sensory systems [3]. Several studies have documented some incredible emotional and physical health benefits that come from touch, starting from the moment we're born [1]. For example, it was found that preterm newborns who received just three 15-minute sessions of touch therapy each day for ten days gained 47 percent more weight than premature infants who'd received standard medical treatment [4]. Studies have also shown that touching patients with Alzheimer's disease can have huge effects on decreasing agitated behaviors [5] or on getting them to relax, make emotional connections with others, and reduce their symptoms of depression [1, 6, 7, 8].

Although we have tended to de-emphasise the role of touch in our own species in favor of language-based communication, there is great evidence that physical touch plays an important role in everyday human relationships [9]. Touch might be considered a form of social communication that crosses cultures, genders, and age groups: it seems that physical touch has emotional and social connotations that can convey the real meaning or intention of an interaction in a way that often can not be expressed in language [10].

Besides being used to establish trust and social bonds with other people, the sense of touch is also a means to gather information about our surroundings. Through the touch we can explore textures, estimate temperature, distinguish different shapes, and assess the location of an object. This is of the utmost importance not only for blind people, but also in any manipulation tasks. Our everyday life is based on exploration and interaction with the environment, and much of this knowledge comes from our limbs and fingers. During environment exploration, the sense of touch is just as important as the sense of sight.

The word haptic, from the Greek haptikos, means “pertaining to the sense of touch” and comes from the verb haptesthai (“to contact” or “to touch”). At the beginning of the 20th century, it was used by psychophysicists to refer to studies on human touch-based perception and manipulation. Later, during the ’70s and ’80s, also robotics researchers began to focus on manipulation and tactile perception and to work on sensory design, grasp control, encoding of haptic information, etc. In the early ’90s, the challenge of creating devices with dexterity inspired by human abilities led to the birth of a new discipline, called “computer haptics”, studying the generation of tactile stimuli and the rendering techniques to the human hand through haptic interfaces [11]. Nowadays, with the term haptic we refer to touch interactions in general, both for perception and/or manipulation of objects, considering the feedback of force, distributed pressure, temperature, vibrations and texture [12].

Haptics is mainly divided into the sensation of forces (kinesthetic perception) and the sensation of skin deformations, vibrations, and temperature (tactile or cutaneous perception) [13, 14]. Through the force feedback we perceive the weight of the objects and their resistance to motion, while the tactile feedback includes the sensation of shapes and textures [15]. The word “kinesthesia” entered the scientific literature with the work of H. Charlton Bastian in 1883 [16]. Literally, kinesthesia is the “sensation of movement” that relies on sensations arising from joints, muscles, and tendons, as well as vestibular sensations. Even if the term kinesthesia refers to the perception of limb movement and position, it is often broadly defined to include the perception of force as well [17].

Kinesthetic and cutaneous sensory systems cannot be considered completely independent. For instance, sensory information about changes in limb position and movement also arises from receptors in the skin and joints. In particular, such inputs seem to be relevant for kinesthesia in the hand, as shown by Edin and Johansson [18], which demonstrated the role of cutaneous feedback in kinesthesia at the proximal interphalangeal joint. Indeed, it was shown that both joint and/or cutaneous anesthesia affect the ability to detect the movements of the fingers and feel their position [19, 20]. Contrarily, for more proximal joints, such as the knee, receptors in the joint or the skin do not importantly contribute to the sensory inflow, but they have only a minor influence on perceived joint angles [21].

In this thesis, we deal with force sensing and contact detection. The first part of this work is placed in the context of restoring the haptic capabilities in scenarios where the natural tactile interaction is hampered due to different reasons. In particular, Chapter 2 and Chapter 3 focus on robotic surgery and present the main idea and the mathematical model, respectively, of a novel pneumatic sensor used to measure the contact force between the surgical instrument and the patient's tissue. Chapter 4, instead, addresses the challenge of measuring and providing to the user interaction forces during drilling tasks in open surgery, in which vibrations generated by the hand-held drill prevent the surgeon from perceiving the exerted force.

In the second part of the thesis, a similar technology will be exploited in less specific robotic manipulation scenarios. Chapter 5 summarizes the state of the art of soft robotics in manipulation and introduces the soft device we developed for this context. Also in this case, Chapter 6 and Chapter 7 describe the working principle and the modeling of the device, respectively.

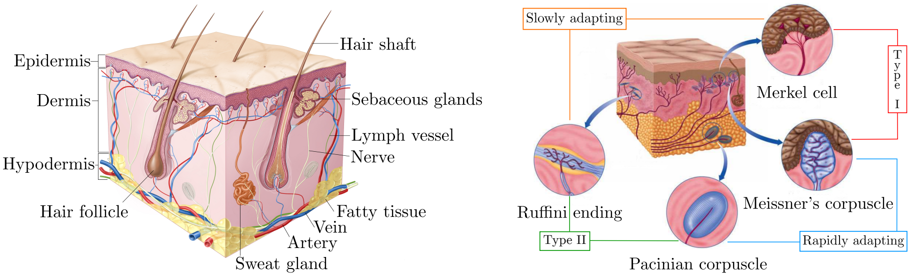
Before going into detail, for the sake of completeness a brief overview on the characteristics of the sense of touch is provided and, then, the motivation of this work is deeply discussed.

1.1.1 Skin and mechanoreceptors

The perception of tactile stimuli is allowed by the touch receptors, which are the sensory neurons that innervate our skin. Besides being the protective barrier between our internal body systems and the outside world, the skin represents the communication channel and the largest organ of the body. Through the skin a person can perceive a wide range of stimuli (e.g., temperature, pain, pressure) and get information about the surrounding world. As shown in Fig. 1.1a, skin is divided in three layers, including, from top to bottom:

- the epidermis, composed of dead skin cells and, thus, not vascularized, which provides a waterproof barrier;
- the dermis, which sustains and supports the epidermis by diffusing nutrients to it and contains nerve endings, hair follicles, sweat glands, sebaceous glands, and a variety of touch receptors;
- the hypodermis, which is made of fat and connective tissue.

Tactile sensations are controlled by a complex system of sensory neurons and neural pathways in the skin, constituting the somatosensory system. It decodes a wide range of tactile stimuli and thus endows us with a remarkable capacity for object recognition, texture discrimination, sensory-motor feedback and social exchange [22]. Four main types of receptors compose the somatosensory system: mechanoreceptors (pressure and surface texture), thermoreceptors (temperature), nociceptors (pain), and proprioceptors (muscle



(a) (b)

Figure 1.1: Human skin: (a) main layers and components, (b) types of mechanoreceptors whose function is to perceive vibrations and indentation of the skin. The main characteristics of each mechanoreceptor (i.e., size of the receptive fields and rate of adaptation) are also shown.

length, muscle tension, and joint angles). Because of the scope of this thesis, among all the receptors, it is worth briefly focusing on the characteristics of mechanoreceptors.

Mechanoreceptors in the skin have traditionally been distinguished on the basis of the types of stimulation to which they respond, the size of their receptive fields, and their rates of adaptation [23]. They can be classified as rapidly adapting (RA), also referred to as fast adapting (FA), if they respond to a change in stimulus very quickly. These receptors are the ones which perceive rapid and regular changes in pressure, such as vibrations, but cannot sense the steady-state contact of a tactile stimulus. On the other hand, receptors can be classified as slowly adapting (SA) if they do not respond to a change in a stimulus very quickly, but they are good at sensing the continuous pressure of an object touching or indenting the skin. Based on the size of their receptive field, mechanoreceptors can be also categorized as type I when their receptive field is small (2–8 mm in diameter) and as type II when their receptive field is larger.

As shown in Fig. 1.1b, there are four major categories of tactile mechanoreceptors:

- Meissner's corpuscles, which are located in the dermis of glabrous skin and adapt rapidly to changes in texture. They are most sensitive in the 20–40 Hz range of vibration and their density is higher on the fingertips (15–24 /mm^2). They are typically associated with RA I afferent fibers [24].

- Merkel cells, which are located in the deepest layer of the epidermis of glabrous skin and detect sustained pressure. Their density is estimated to be 80 /mm^2 and they are typically associated with SA I afferent fibers [25].

- ◇ Ruffini endings, which are located in the deepest part of the dermis of both hairy and glabrous skin. They respond to pressure on skin and are very sensitive to pressure variations. They are typically associated with SA II afferent fibers [26].
- ◇ Pacinian corpuscles, which are located deep within the dermis and the subcutaneous fat layer of both hairy and glabrous skin. They detect rapid vibrations (the highest sensitivity is in the range 200–550 Hz). They are typically associated with RA II afferent fibers [27].

After a brief introduction on the main features of the sense of touch from a physiological point of view, we can go deeper into the discussion of its reproduction and addition in the field of robotic manipulation. For humans, touch plays a vital role for tasks involving contact with objects without damaging them. Augmenting robots with the sense of touch could remove uncertainties in manipulation tasks, especially in dealing with soft, fragile and deformable objects. For the last decades robotics researchers have worked to create an artificial sense of touch to give robots some of the same manipulation capabilities that humans possess [28]. Even though autonomous robots mainly rely on some form of visual perception to interact with the surrounding environment, there are tasks that would be impossible or too complicated without the sense of touch [29].

1.2 Bilateral teleoperation

Haptic technology has been typically needed in robotic teleoperation to measure and transmit pieces of information at/to a different site. Teleoperation systems are employed to sense and mechanically manipulate objects at a distance by virtually relocating the operator at a place other than his/her true location [30], allowing access to inaccessible, hazardous, or scaled environments. Teleoperation systems are composed of a slave robot, which interacts with a remote environment, and a master console controlled by a human operator. The slave robot mimics the movement of the operator, which in turn needs to observe the remote environment the robot is interacting with. Thus, the slave side is equipped with sensors to perceive the surrounding environment and actuators to interact with it, while the master system includes sensors to detect the human commands and actuators to feed back remote information to the operator. The communication between master and slave is enabled by a network channel.

Since teleoperated systems generally lack of any haptic feedback, users usually rely only on visual observations. However, studies have shown that operator performance increases significantly in telemanipulation of remote objects when haptic feedback is provided [31]. Sheridan has conducted experiments on automation and planning of complex tasks through human supervisory control and has shown that the task completion times can be reduced with haptic feedback [32]. It also appears that touching and manipulating objects improves the subjective experience. Durlach and Slater emphasized that touch, in comparison to other sensory modalities, is more local and bidirectional and, thus, it is linked to closeness and intimacy [33].

The lack of haptic feedback in current master-slave systems is an important issue in performing very precise and accurate tasks, such as surgical procedures, where this missing feature can be considered as a safety risk because it can lead to accidental tissue damages. Force feedback has been shown to enhance operators' performance of teleoperation frameworks in terms of completion times of a given task [34, 35, 36], accuracy [35], and peak [37, 38] and mean applied force [36, 38]. In medicine, improved performance when providing force feedback was demonstrated in a wide range of applications including fine microneedle positioning [39, 40], suturing simulation [35], telerobotic catheter insertion [41], palpation [42], cardiothoracic procedures [43], keyhole neurosurgery [44], endoscopic surgery [45], and cell injection systems [46]. For these reasons, robotic minimally invasive surgery can be considered one of the most representative examples of teleoperation scenarios suffering from the reduction of haptic perception.

1.3 Force sensing in surgical procedures

1.3.1 Robotic minimally invasive surgery

Robot-assisted minimally invasive surgery (RMIS) is increasingly becoming a fundamental component of the state of the art operating room. It might be considered the evolution of the manual minimally invasive surgery (MIS), as surgical instruments and cameras penetrate the patient's body through small incisions. However, differently from laparoscopic surgery, RMIS allows surgeons to perform complex procedures at a distance, by remotely controlling robotic arms which directly interact with the patient's body. Indeed, surgical robots represent an example of master-slave system, in which the instruments used on the patients (slave side) are not physically connected to the handle controlled by the surgeon (master side), but reproduce its movements [47]. Thus, the most important difference with traditional surgery, both open and laparoscopic, is that the surgeon is not at the operating table but controls the instruments from a nearby console, looking at the surgical area through a monitor.

The first surgical robot was the Da Vinci, developed by the Californian company Intuitive Surgical and used in operating rooms since 2000. It is mainly employed in prostate removal procedures, heart valve replacement, gynecological surgery, and also in general abdominal or thoracic surgical procedures. Over the past 20 years, RMIS has been increasingly developed with the aim of improving precision, reducing errors and incision size, and facilitating recovery after surgery both in terms of duration and pain [48]. Its success is due to several different reasons, e.g., improved flexibility and control, reduced instruments tremor, error-free and timely repetitive tasks execution, less blood loss, and fewer complications such as surgical site infections. Among the multiple advantages of robotic surgery, the enhanced visualization, due to a complex vision system, allows the surgeon to have a complete and high definition view of the operating area.

On the other hand, there are still a few disadvantages with respect to the manual minimally invasive surgery, in which surgeons feel the interaction between the surgical instrument and the patient via a long shaft. Although also in MIS tactile cues and force feedback in general are deprived compared with open surgery [49] (they result weaker and a bit unrealistic), in RMIS any natural haptic feedback is generally absent, i.e., the surgeon is no longer in contact with the instruments entering the human body. Despite the number of advantages offered by RMIS over traditional surgery, it is reported that the lack of haptic feedback, thus the missing feature for the surgeon, is one of its main limitations [48, 50, 51, 52].

1.3.1.1 The lack of haptic feedback

Palpation is the process of examining the human body using the hands and is considered a real diagnostic tool. It is usually performed by health care practitioners to diagnose diseases and illnesses and consists in touching the body to feel tissues/organs and determine their size, shape, firmness, and location, combining visual information to tactile sensations. By touching the area of interest it is possible to determine the main characteristics of the tissue, depending on the exerted deformation and the perceived force [53]. It can be done with one or two hands, both on the skin and on the patient's internal tissues. Palpation may be helpful to identify irregularities of the abdominal wall (e.g., hernias), locate anatomical landmarks to identify structural irregularities, such as a joint dislocation, determine the position of the fetus during pregnancy, or examine irregularities suggestive of a tumor.

Regarding the last point, the role of palpation is fundamental in tumors localization procedures. During open procedures, clinicians have direct access to anatomical surfaces and can manually investigate their consistency to detect abnormal tissues [54], recognizing as potentially abnormal and tumorous those tissues stiffer than the surrounding anatomical areas. In fact, usually cancer masses are less flexible and elastic than non-malignant ones, which are softer and with well defined margins. RMIS systems have hampered these fundamental palpation procedures because of the physical separation between master and slave side. This loss of haptic sensation prevents surgeons from properly detecting local mechanical properties of tissue such as compliance, viscosity, and surface texture, that can indicate the current status of the tissue, i.e., healthy and non-healthy [12]. At present, interaction forces during robotic surgery can only be estimated by observing the deformation of the tissue on the images of the endoscopic cameras [55], but compensation by visual feedback does not prevent from inaccurate discrimination.

Haptic information is also required to preliminary decide if the interaction between the surgical tool and the tissue has to necessary be gentle, without exceeding determined contact force threshold values, to prevent damages such as accidental puncturing of blood vessels. It can be important also to feel the consistency of a blood vessel in order to assess the presence of deposits. Moreover, haptic cues can play a primary role in enhancing precision when complex kinematics and low maneuverability instruments are at hand, and in speeding up actions of surgeons, since they no longer rely on visual feedback only and can also know some mechanical properties of tissues, e.g., softness. As an obvious consequence, the absence of force feedback leads prolonging and hampering the natural conduct of the operation [56]. Another benefit of haptic feedback is that the central nervous system processes and responds to tactile stimuli faster than visuals [57].

Many studies pointed out the clear benefits of haptic feedback restoration in several clinical applications [52], and also during the training phase of robotic surgeons [58]. Wagner et al. [38] have been among the first to systematically assess the benefits led by force feedback on blunt dissection using robotic surgery: the absence of haptic feedback increased errors causing tissue damage by a mere factor of 3, proving that haptic guidance prevented operators from applying excessive forces. They proved that without force feedback the average force applied to the tissue increased by at least 50%, while the peak force increased by at least a factor of 2. Meli et al. [59] proved that haptic feedback (even magnified) enhances the performance of a teloperation framework during robot-assisted needle insertion and palpation tasks. Pacchierotti et al. [42] tested different types of tactile feedback in a teleoperation framework in which eighteen subjects used a Da Vinci robot (Intuitive Surgical Inc., USA) to palpate a heart model. Fingertip deformation feedback significantly improved palpation performance by reducing the task completion time, the pressure exerted on the heart model, and the subject's absolute error in detecting the orientation of an embedded plastic stick. Mahvash et al. [60] exploited again a Da Vinci Surgical System (a customized version) to prove that direct force feedback is superior to graphical force displays in a palpation task of both a heart and a prostate models. The lack of force sensors on the slave side of the system seriously affected surgeons' identification of hard inclusions inside artificial tissue models. Moody et al. [35] showed that the accuracy of sutures improved with the use of haptic feedback, reducing also task completion time. Furthermore, haptic information could also be beneficial for enhancing surgeon perception of the incision depth: in [61], the authors showed that combined kinesthetic/vibrotactile feedback could increase accuracy compared to visual feedback.

We can conclude that, despite some basic information on the environment can be acquired by simply observing visually the response of tissues or materials (such as sutures) to the movements of the surgical instruments [12], it has been demonstrated that restoring the haptic capability in RMIS contributes to improving accuracy and safety [38]. For this reason, many studies had the purpose of designing systems able to detect and convey to the surgeon the exerted forces. One the one hand, a sensor is needed to measure the forces exerted on tissues and bones of the patient's body. On the other, a device is required that allows the surgeon to directly perceive these forces on the hand.

1.3.2 Force sensing techniques in RMIS

In any teleoperation scenario the force applied on the slave side needs to be measured, or at least estimated, in order to be fed back to the operator. In robotic surgery, although a great effort has been made by researchers to develop novel haptic interfaces able to provide force feedback to the surgeon, far fewer works exist regarding the design of sensing systems. Indeed, any attempts to measure or estimate forces applied during robotic surgery had to face technical challenges.

Many researchers used commercially available force/torque sensors, which are very effective to accurately measure such interaction forces in many teleoperation applications, but are not always suitable for RMIS due to constraints in terms of size, cost, biocompatibility and sterilizability [53, 62, 63].

The small incisions through which the instruments penetrate the human body place a severe constraint on the diameter of the terminal portion, whose size should not exceed 10–12 mm. Commercial force sensors are usually larger than 12 mm and can not be placed in the portion of instrument entering the human body.

Surgical instruments that penetrate the human body are subjected also to strict sterilizability constraints: unless they are disposable tools, it is essential that the instruments are properly cleaned in order to prevent infections. A standard method consists in steam sterilization in autoclave to heat the equipment up to 121 C at 103 kPa above the atmospheric pressure for at least 15 minutes. Such high temperature and pressure are required to ensure complete destruction of microbial life forms but, unfortunately, the intensive heat, pressure, and humidity can also potentially destroy sensors, electronics, and even insulators of simple electric wires [64]. Currently available force sensors include electronic parts that do not tolerate the severe sterilization conditions required in case of reusable medical devices.

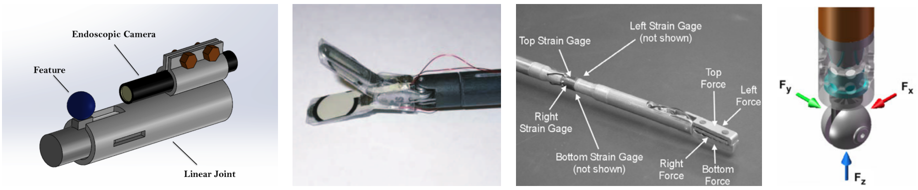
1.3.2.1 Force sensing through vision: state of the art

The easiest way to match all the operating theater constraints consists in using vision to track tissue deformation and consequently estimate its mechanical properties and interaction forces. No add-on sensors are needed, because standard endoscopic cameras already integrated in the robotic system might be used. In this way, the sensing method would be less invasive and overcome the constraints on size, cost, biocompatibility, and sterilizability.

Different approaches have been studied to model tissue deformations. One among all uses deformable active contours, also called snakes, to observe changes over time [65]. The minimization of the energy function, depending on contour smoothness, image forces, and external constraint forces, has been fused with a prior knowledge from finite element models of non-linear elastic materials. This method, however, requires the knowledge of physical parameters of human organs that are not always available [66]. Aviles et al. [67] used again energy functional minimization to measure the tissue surface displacement, but they exploited also a neuro approach to establish a geometric-visual relation and estimate the applied force. A significant accuracy improvement ranging from 15.14% to 56.16% was demonstrated with respect to others methods. In [43] the authors tracked the deformation of a rubber membrane in real-time through stereovision while providing haptic feedback to the user interacting with the reconstructed membrane through the PHANToM haptic device. Again, to calculate the surface force, a priori knowledge of the material properties is needed.

Most of the research studies on force estimation using vision techniques have focused on interaction forces acting during hand-object manipulation: they can be estimated using a RGB-D camera, assuming to know both the hand geometry and object properties like shape, contact friction, mass, etc. [68]. Also in this case it is difficult to exploit such approaches to measure forces exerted by surgical instruments on organs and tissues, due to the lack of accurate information about their properties.

In general, the challenge in applying artificial vision techniques to the human body is related to the difficult estimation of the deformations without an a priori knowledge of the non-deformed object properties. However, it is possible to apply some of these techniques in surgical scenarios changing the approach in order to focus only to the instrument and not to the human body. One solution may be to exploit vision softwares to observe changes in the shape of one or more elements belonging or connected to the surgical instrument. For example, Faragasso et al. [69] proposed a system combining vision and a spring mechanism to relate the variation of the size of a certain feature to the estimated force (see Fig. 1.2a).



(a) (b) (c) (d)

Figure 1.2: (a) Force sensing device composed of a linear retractable mechanism and a spherical visual feature: as the distance between the camera and the feature varies due to the sliding joint, interaction forces with anatomical surfaces can be computed based on the visual appearance of the feature in the image [69]. (b) Piezoresistive force sensors mounted on the gripping surfaces of the surgical instrument [70]. (c) Strain gauges placed on the shaft of the laparoscopic tool [71]. (d) A sensor employing an optical fiber sensing scheme to perform tissue interaction force measurements using pairs of bent-tip optical fibers, nonmetallic reflectors, and a monolithic flexible structure [72].

1.3.2.2 Force sensors: state of the art

Even though most of the surgical tools were not designed to host sensors, some researchers have had success in integrating them to existing jaws or to the tip of grasping forceps [73]. For example, King et al. [70] developed a modular pneumatic haptic feedback system to improve the performance of the Da Vinci surgical system. It includes piezoresistive force sensors mounted on the gripping surfaces of a robotic tool (as shown in Fig. 1.2b) and two pneumatic balloon-array tactile displays mounted on the master console. However, for sterilizability reasons, sensors should not be mounted directly on the jaws because it is desirable to use tips that can be detached and disposed of after use. In this regard, Tavakoli et al. [45] placed several strain gauges on the base of an endoscopic end-effector far enough from the tip to non-invasively measure interactions with the tissue. The use of strain gauges has been proposed also by Sarmah et al. [71], as shown in Fig. 1.2c.

A different approach can be to re-design surgical equipment. In this direction, Gonenc et al. [74] presented one of the first micro-forceps for retinal microsurgery that can sense 3-DOF forces at the tool tip. Puangmali et al. [72] developed a rolling device instrumented with a miniature three-axis distal force sensor based on a optical sensing scheme and capable of measuring tissue interaction forces within measurement ranges of ± 3 N in axial direction and ± 1.5 N in radial direction (see Fig. 1.2d).

Other approaches of force measurements used light modulation techniques [75] or elastomer elements [76]. A biomimetic tactile sensor is presented in [77]: deformations of its skin can be detected by displacing a conductive fluid from the vicinity of electrodes on a rigid core. While the sensor is promising in providing human-like haptic capabilities for surgical robots, it is still not compatible with robot-assisted surgical operations due to its on-board electronics and poor possibility of sterilization.

After discussing the state of the art on sensors for measuring interaction forces in robotic surgery, four possible locations where to place the sensing device have been identified and evaluated:

- In proximity of or at the actuation mechanism driving a joint. It is possible to measure the forces acting at the tip of the instrument by measuring the stress on the mechanical linkages or the responses of the actuators, if the surgical instrument has actuated joints. However, the effects of these forces are transferred through mechanical linkages, and factors like friction and inertia could distort the force values causing measurement errors;

- On the instrument shaft outside the patient's body. This portion of the instrument does not enter the body through the insertion port, thus, it has not to face constraints of size or materials. In this case, a drawback is that the sensing element would be subjected to friction and reaction forces generated at the instrument insertion port, which could be considerably higher than the interaction forces between instrument tip and tissues. Without considering friction compensation, it is not possible to measure contact forces exerted on tissues.

- On the portion of the instrument shaft inside the patient's body and before the tip. This is one of the most suitable positions to place a sensor because frictions and reaction forces generated at the insertion port do not affect the measurement. Space limitation represents the major disadvantage: to pass through the insertion port, the maximum diameter should be 10–12 mm.

- At the instrument tip, such as on a gripper jaw. Among all the possible positions, this is the one where the forces acting on the instrument tip can be most directly measured. Friction and other disturbance forces generated from any moving mechanisms do not affect the measurement of the tissue contact forces as much as that in the other cases. Unfortunately, the tip is the place that exhibits most severe space limitations: only very small sensing elements or instruments which have a large gripper can be considered [64].

After considering advantages and drawbacks of each location, we decided to implement a different strategy exploiting a novel sensor whose working principle will be explained in Chapter 2.

1.3.3 A pneumatic method to measure contact forces

In Chapter 2, a new pneumatic based method to estimate the contact force between surgical instruments and tissues is presented. The proposed sensor consists of a tiny pneumatic balloon hosted inside the surgical tool and used to palpate the tissue as the surgeon's remote fingerpad. After being inflated, it appears near the tip of the instrument during the measurement phase only. Once it comes into contact with the human tissue, a change in the air pressure inside the balloon is registered by a pressure sensor. This value is proportional to the norm of the contact force. The working principle and the preliminary results obtained in Chapter 2 have been then extensively studied in Chapter 3 with the aim of finding a mathematical model relating the norm of the contact force to the variation of pressure inside the membrane.

The investigation on the relation between force and variation of air pressure in a balloon paved the way for the development of novel sensors that can be used also in different applications. For example, a pneumatic working principle has been exploited in a novel tool for bone drilling procedures in open surgery, as described in Chapter 4.

1.3.4 Force sensing for hand-held drilling tools

Technological advancements in surgical tools and increasing health care demands have expanded the field of robot-assisted surgery to newer specialties. Even if the achievements in the last years have been impressive and it has been proved that restoring the haptic capability in robotic surgery contributes to improve accuracy and safety in performing complex and delicate surgical tasks [38], current robotic surgical systems are still limited by the lack of haptic feedback, as detailed in Section 1.3.1.

On the other hand, also open surgery may suffer from a reduction of tactile perception. In fact, even if during open procedures surgeons directly interact with the patient's body, some surgical tools, e.g., drills, may limit the haptic perception. Thus, despite the direct access to anatomical surfaces, drilling of a bone is an example of open procedure in which surgeons are not able to clearly perceive the interaction between the surgical instrument and the patient, due to the high rotational speed and vibrations. As a matter of fact, a common issue in surgical drilling is that vibrations generated by the tool affect the perception of the surgeon, reducing, for instance, the capability in discerning different tissues and detecting the break-through force [78].

Bone drilling is a task required in many medical disciplines such as orthopedic, ear, maxillofacial, and neurological surgeries [79]. In this thesis, we focus on otologic procedures, where a precise control of the surgical drill is required because the critical anatomy within the middle ear, inner ear, and skull base can be accessed by drilling

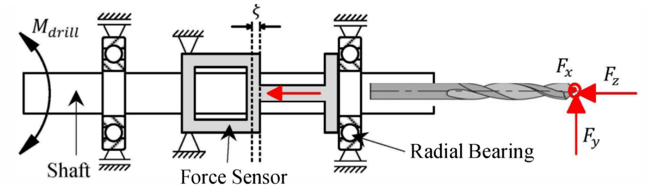
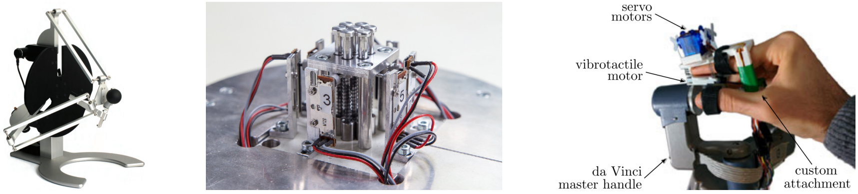


Figure 1.3: Mechanical structure of a drill with force sensor integration [81].

within the temporal bone for operations which demand high precision and accuracy [80].

Several researchers pointed out the benefits of restoring haptic feedback in hand-held drilling procedures [82]. For instance, in [83], force sensing has been elected as the appropriate way to obtain controlled penetration in the patient's body and automatic discrimination among layers of different tissues. The authors presented a hand-held drilling tool devoted to orthopedic surgery, where the chuck shaft transmits the thrust to a force sensor made by a steel cantilever spring, the deformation of which is measured by means of a Wheatstone's bridge of foil extensimetric resistors. In [84], Du et al. developed a smart surgical drill that is able to control interaction with the tissue, maintaining a constant low level of force during the drilling process by manipulating the linear movement (out to in) of the drill. Ong et al. [85] proposed a reliable method of break-through detection when drilling into long bones. In [81], the authors integrated a thrust force sensor into the drill (see Fig. 1.3) in order to enable high accuracy during pedicle screw positioning. Their sensor is designed to measure the axial thrust force of the drill bit without transverse forces.

In the aforementioned works, the force measurement is obtained integrating sensors into the mechanism of the tool. In Chapter 4, we propose a pneumatic method to measure the contact force between the drill bit and the bone without modifying the internal structure of the drill, with the aim of creating an instrumented cover that can be easily customized and adapted to the off-the-shelf hand-held drills. To the best of our knowledge, this represents the first attempt to assist a surgeon with haptic feedback in open surgery without modifying the existing equipment.



(a) (b) (c)

Figure 1.4: Examples of (a) grounded haptic interface providing kinesthetic feedback [86], (b) tactile display relying on metallic pins to provide cutaneous sensations [13], (c) wearable device providing cutaneous and vibrotactile feedback [42].

1.4 The haptic display

Besides the sensing system, the other essential component for the force feedback is the haptic device used to convey the information to the user. In Chapter 4, we exploited a haptic ring capable of generating cutaneous and vibrotactile feedback, to test the effectiveness of haptic feedback during drilling tasks. Even if the reproduction of force/tactile stimuli is not the main focus of this thesis, some of the most significant studies in literature have been reported for the sake of completeness.

Direct force feedback in teleoperation systems can use conventional force display technology, in which the motors of the master manipulator are programmed to recreate the forces sensed by the robot [12]. DELTA.6 [86], PHANToM [87], and Spidar [88] are types of grounded haptic displays that apply proprioception on the arm via a stick or a ball driven by motors. Among wearable haptic devices, glove-type haptic displays such as Rutgers Master II can provide force sensations to all five fingers of the hand simultaneously [89].

Besides kinesthetic feedback, several devices have been developed that provide cutaneous feedback. One of the most common types of tactile display is an array of pins that are individually actuated, so that it is easy to map data recorded by an array-type tactile sensor to the position of each pin [90]. Hergenhan et al. [13] presented a haptic display that features seven pins mounted on compression springs that can be pre-loaded with servo motors. A similar device has been used by King et al. [70, 91], which have substituted the metallic pins with pneumatic balloon of 3 mm diameter. In contrast to the sensing system, in which the use of pneumatic balloons to measure forces is innovative, such technology is common at the master side: in several works, pneumatic balloons have been used as a part of the tactile display [92, 93, 94].

Minamizawa et al. [95] proposed a wearable haptic display to convey the weight sensation of a virtual object. This device is based on the insight that the deformation on fingerpads makes a reliable weight sensation even when the proprioceptive sensation is absent, proving that kinesthetic and cutaneous sensory systems influence each other. In this context, many cutaneous feedback techniques for teleoperation have been presented in the literature, exploiting the different types of cutaneous stimuli that mechanoreceptors in the skin can detect. A further example has been proposed by Pacchierotti et al. [42], which presented a cutaneous device rigidly attached to the manual controller of the Da Vinci surgical robot, with three servomotors orienting and translating a mobile platform in three-dimensional space to apply planar fingertip deformation and a vibrotactile motor conveying vibrations to the fingertip. Fig. 1.4 shows three significant examples of haptic displays.

An alternative approach is to exploit sensory substitution to display force, including audio feedback [96, 97, 98] and graphical feedback [62, 99, 100, 101, 102, 103]. A graphical force display could be a viable solution in robotic surgery, where the surgeon already looks into a monitor to have a view of the surgical site. However, when information about the force is provided to the user through visual signals, it should be considered that the surgeon could be distracted from viewing the patient via the endoscopic camera. Even more so, during open procedures the surgeon has to look directly at the patient's body and a monitor could be distracting. To increase the efficacy and the immersiveness of the force perception, a device which does not change the sensory modality but allows the natural perception on the hand, like a vibrotactile device, would be preferred. For example, some studies from the teleoperation literature proved that visual feedback was not as effective as vibrotactile feedback [104, 105]. For this reason, in Chapter 4 the proposed system is capable of rendering the force feedback to the user by means of a haptic ring exploiting cutaneous and vibrotactile sensations.

Chapter 2

A novel pneumatic force sensor for robot-assisted surgery

In this chapter a pneumatic-based force sensor is presented, to measure the force generated at the tip of a surgical instrument during robot-assisted minimally invasive surgery (RMIS). As detailed in Chapter 1, despite the achievements of the robotic surgery, the lack of haptic feedback to the surgeon is still a great limitation, since through palpation the physician can distinguish consistency of tissues and determine the occurrence of an abnormal mass. Although a great effort has been made by researchers to develop novel haptic interfaces able to provide force feedback to the operator, far fewer works exist regarding the design of sensing systems for robotic surgery. In this respect, we propose a new force measurement method based on the relation between the air pressure variation inside a pneumatic balloon and the interaction force due to the contact between the balloon and an object. The balloon can be placed in a cavity of either the surgical instrument or the endoscopic camera. Due to the contact between the balloon and patient's body, a change in the air pressure inside the balloon occurs. This difference in pressure can be related to the interaction force. A performance comparison with a very-fine resolution commercial force sensor proved the feasibility and effectiveness of the proposed approach.

While several tactile displays using pneumatic balloons have been developed for RMSI applications [91, 93], to the best of our knowledge, such an approach is totally underexploited on the sensing side. Furthermore, the novelty of pneumatic balloons used as force sensors is not only in RMSI frameworks, but also in more general teleoperation scenarios.

2.1 Pneumatic force sensing

This section focuses on explaining the idea of using a tiny pneumatic balloon to estimate the interaction forces playing on the slave side during robot-assisted surgery. As explained in Chapter 1, due to the strict constraints of the operating room, it is not trivial to measure

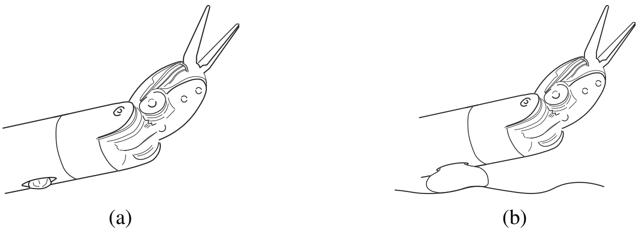

(a) (b)

Figure 2.1: Working principle of the proposed pneumatic force sensor. (a) A pneumatic elastic membrane is hosted deflated inside the surgical instrument when it is not needed. (b) When a measurement of the interaction force is required, the membrane is inflated and comes into contact with the human tissue. The subsequent change of pressure of the internal gas is then related to the instrument/tissue interaction.

forces occurring during instrument/tissue interactions. In this chapter, we propose an innovative approach to evaluate those interaction forces, taking advantage of a tiny pneumatic balloon hidden inside the cavity of a surgical tool when not used. By inflating the elastic membrane with a gas, e.g., air, it comes out very close to the tip of the surgical instrument and can be used to palpate the human tissue of interest, as sketched in Fig. 2.1. During the exploratory approach to the patient's body, the surgeon needs information about the consistency of soft tissues and masses. To this purpose, the balloon acts as the remote surgeon's fingerpad, permitting also those palpation tasks often essential in open surgical procedures, e.g., locating arteries.

Many advantages of this approach can be appreciated from different points of view. First of all, the elastic membrane can be made of biocompatible material already widespread in surgery, such as latex, polyurethane, or silicone, in order to prevent any kind of inflammation or immune response against the material itself [106, 107]. Secondly, all the parts that need to be embedded in the surgical tool and that enter the human body are simple and very inexpensive. Since most of the surgical tools, e.g., da Vinci tools, are disposable because of sterilizability reasons, the sensing system must not represent a further significant cost. Indeed, in the proposed sensing apparatus, the electronic sensors and boards are not located in the operational workspace and do not need to be replaced at the end of the operation. This is possible because mechanical information is transferred by means of a gas to the sensitive components. The use of a pressure sensor, whose size is comparable to the one of commercial force sensors available on the market, does not present the same limitations discussed in Section 1.3.2.2. The different measuring principle allows us to place the sensor even far from the contact site, differently from common force sensors, avoiding the disposal of the sensor at the end of any surgical intervention. Pressure is uniformly distributed in the whole pneumatic circuit and, thus, it is possible to place the sensor in several different configurations, depending on the available space, as long as the sensor is connected to the pneumatic circuit of the balloon. For example, it would be possible even to place the pressure sensor into the robotic arm that holds the instrument.

A further advantage of the proposed device is that the pneumatic balloon comes out from its housing in the proximity of the end-effector tip only when the elastic membrane is inflated, without limiting or constraining the tool workspace when it is not needed. Moreover, another interesting feature is the possibility to set the inflating pressure so as to have a sensor with different stiffnesses depending on the anatomical area. However, it is important to have the balloon always more compliant than the tissue so that the deformation caused by the contact occurs mostly in the sensing system.

Finally, the elastic membrane, because of its nature, adapts to any curvilinear surfaces of the body: this may represent a further advantage, because human tissues may have an irregular shape and different stiffness. A sensor that can passively adapt to the body part being touched avoids unreliable and non-continuous signals that might be delivered by standard single-point contact sensors. Nevertheless, as discussed below in Section 2.2.4, the relation between force and pressure is independent from the contact surface as long as there is no indentation of the membrane. This may be caused by very pronounced and localized irregularities, which however are extremely rare in the areas of the human body usually explored in robotic surgery.

When all the force information is successfully collected by the surgeon, the balloon can be deflated again and hidden inside its housing to avoid limiting surgical instrument tip motions. The surgeon can repeat the aforementioned palpation action anytime it is deemed necessary.

2.1.1 Device description

In this chapter, we present a proof of concept in which the pneumatic force sensing system is composed of a 3D-printed part made of ABSPlus (Stratasys Inc., USA), a latex pneumatic balloon, an air compressor Ciao 25/185 (FNA S.p.A., IT), two solenoid valves L172 2/2 G1/8 (Asco Numatics Sirai S.r.l., IT), a differential pressure sensor MPXV5050DP (Freescale Semiconductor, USA), an Arduino UNO board (Arduino, IT), and some pipes and airtight fittings to connect the different components. The idea is to have a system composed of two main parts, one characterized by a rigid structure (valves, pressure sensors, controller) and another more flexible (pipes and pneumatic balloon).

The tank air compressor equipped with a pneumatic pressure regulator prevents the

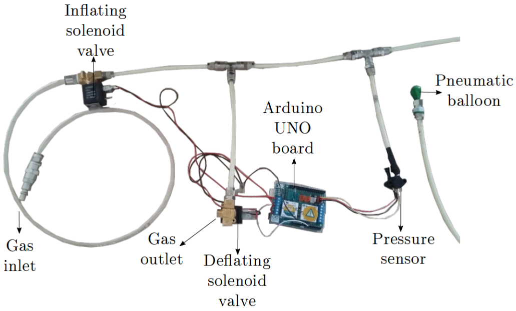


Figure 2.2: The pneumatic circuit used to validate the proposed sensing method.

occurrence of blast waves in the air inside the circuit. The addition of two solenoid valves, whose control is managed by the Arduino board, enables the operator to control the air flow, inflating and deflating the circuit according to the desired pressure value. The opening/closing time of the valves is 10 ms. It is essential that all the hoses and couplings are leakproof to avoid undesired pressure variations that might severely affect sensor readings. The exploited differential pressure sensor has a pressure range of (0, 50) kPa and an accuracy of 2.5 % of full scale.

2.1.2 Pneumatic system control

We herein report a brief description of how the micro-controller Arduino Uno, combined with the Arduino 4 Relays Shield, manages the opening and closing of the solenoid valves and induces different system conditions: i) inflating, ii) deflating, and iii) locking.

Inflating and deflating procedures open the inflating and deflating valves (see Fig. 2.2), respectively, keeping close the other one. While during both these policies the amount of air present inside the system changes, in the locking condition the two solenoid valves are closed and the amount of air inside the system is constant. The operator can arbitrarily choose in any moment to start the inflating or deflating actions or change the desired pressure value. In the latter case, an automatic procedure will open/close the valves to reach the preset air pressure inside the system and keep it constant. To prevent the chattering of the internal pressure when close to the preset value, that might lead to a malfunction of the whole measuring system, we introduced hysteresis adopting two different thresholds equal to the desired pressure ± 0.1 kPa. To compensate pressure fluctuations the sensor output signal has been also processed through a first order exponential filter.