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Pneumatic Actuation in Haptic-Enabled Medical Simulators: A Review

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ABSTRACT Haptic feedback is essential for achieving virtual and augmented reality (VR/AR) systems with high fidelity and realism. Haptic-enabled VR/AR systems offer a proficient environment in which to enhance the skills of medical practitioners. While pneumatic actuation is traditionally used in heavy automation industries, haptics researchers have utilized pneumatic techniques to produce various haptic effects, i.e., stiffness feedback and contour control, and these techniques have shown promising results in the medical domain. In this paper, we focus on the use of pneumatic-actuated haptic systems in VR/AR-based medical simulators. We begin with the taxonomy of the physical-virtual continuum and discuss the role of pneumatics in medical haptic systems. Furthermore, we propose the conceptual design architecture of a pneumatic haptic system. In addition, the systematic state-of-the-art role of pneumatic haptics in medical systems is presented for different categories. In this paper, we provide a systematic review and discuss the study of pneumatics to provide guidelines for the design and development of pneumatic haptic medical systems.

INDEX TERMS Augmented reality, haptic interfaces, medical simulation, pneumatic actuators, pneumatic systems, virtual reality.

I. INTRODUCTION

Haptics, which involves the study of the sense of touch, is an emerging field gaining significant attention from many areas of research, such as surgical robotics, virtual reality, medical training, telerobotics, and gaming. Generally, haptic interaction involves a touch (physical contact), which is usually followed by the perception or manipulation of objects in either real, virtual, or remote environments [1]. In most cases, the sense of touch resulting from the interaction with these objects should be provided with high fidelity and realism to attain the goal of a haptic system.

One of the most prominent areas of research that crucially requires high-fidelity haptic feedback is that of medical simulators (MSs). In general, medical training simulators require providing realistic subtle differences in haptic properties among various soft tissues since, in many cases, the main task of a medical procedure is to discriminate between these differences in real organs. Combined with realistic visual feedback, a haptic-enabled medical simulator plays an important role in training medical students due to its ability to simulate various medical cases efficiently. In addition, with integrated sensing technologies, MSs are useful tools for determining and managing a physician's level of skill and knowledge and for transferring sensorimotor and knowledge skills adaptively [2], [3].

The realism of medical simulators has relied on the physical-virtual spectrum [4], [5]. In this spectrum, there are two different extremes: physical simulation and virtual simulation, as shown in Figure 1. Physical simulation relies only on physical mock-ups that resemble, in terms of visual, haptic, and functional properties, real body parts. The degree of this resemblance is one of the core performance measures of the mock-up-based simulation. Traditionally, medical schools have used this mock-up-based simulation for training purposes. Commercial products, which usually have a very limited number of demonstrated abnormalities, are available. The lack of reconfigurability sometimes prevents effective learning.

The other extreme, i.e., pure virtual simulation, has also been extensively studied and investigated. Every type of feedback, including visual, aural, and haptic signals, is computationally simulated and synthetically reproduced by computers and human-computer interfaces. Since all of it is synthetic, the feedback is very flexible, and additional cues for training

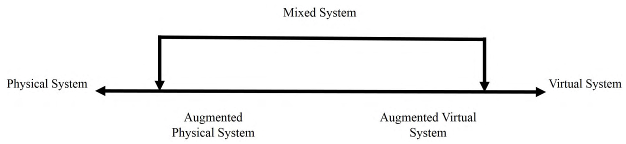

FIGURE 1. **Taxonomy of the physical-virtual continuum in a system [4], [5].**

can be added to the feedback, e.g., virtual guidance. However, the main drawback is the lack of feedback fidelity due to the following reasons: low interface performance, exceedingly high simulation complexity with limited computational power, and lack of data and models for simulation. In particular, haptic simulation and rendering of a deformable surface, e.g., tissue, requires extensive real-time computations, which are sometimes impossible to carry out. Taking the advantages of the two examples, mixed simulation, also called augmented simulation, lies in between physical and virtual simulation [6].

Augmented simulation adequately mixes real and synthetic haptic feedback to create the desired complex feedback with high fidelity. For example, the body parts of a mannequin offer a physical medium, which is similar to a typical patient case, while a programmable haptic organ can flexibly synthesize different symptoms. A well-manufactured mannequin can offer a very realistic physical touchable presence without any computational load or sophisticated haptic device, which is hard to achieve in a virtual simulation, while additional virtual feedback offers flexibility. This mixed simulation approach is ideal for medical procedures where only a small area of interest needs to be dynamically changed while the rest remains static.

One of the approaches to developing a mixed simulator is to embed a haptic system for virtual feedback into an existing mock-up system. Since existing systems have already been tested and their specialization for a specific environment has already been proven, high fidelity is ensured for static surroundings. The embedded haptic system can be either an already existing commercialized haptic device or a specially designed haptic device. Various commercial haptic devices that can produce the perception of force and stiffness at the haptic interface point (HIP) in a specific workspace are available. The literature provides evidence of the use of commercial haptic devices in mixed simulations [3]. The existing commercial haptic devices completely support virtual and augmented virtual simulations. However, some of the restricted features of conventional haptic devices, e.g., they provide only a point-contact interaction, large form factor, and limited workspace, may not fully support mixed simulation. For instance, large haptic devices are not suitable for use in a human body torso. Therefore, suitable machine designs are required to overcome the limitations of the existing devices.

The manufacture of such a haptic device for mixed simulation falls within the realm of machine haptics. Machine haptics can be described as a complementary study of machine design. Machine haptics incorporates advanced technology to mediate tactile communication between human beings and computers [7] to replace or augment human touch. Machine haptics can resolve many challenging issues related to the restricted use of tactile devices. Therefore, machine haptics combines mechanical, computer, control, and electrical engineering. This multidisciplinary field of engineering is also known as mechatronics [8]. In addition to traditional electronic motors, machine haptics involves different technologies such as pneumatics [9], hydraulics [10], ultrasonic technology [11], and magnetic-field control [12], which provide ways to obtain tactile and kinesthetic feedback as per the required configuration. All machine haptic technologies contribute to achieving high system accuracy and performance.

Among the various technologies used to build a haptic interface, this paper focuses on the use of pneumatic actuators, especially for the purpose of medical haptic simulation. The desired property of haptic medical simulators is to provide a learning resource with high fidelity and realism. However, the use of physical and virtual simulators does not provide an elevated commitment to realism. Therefore, the enhanced physical and augmented virtual simulator is needed to overcome this limitation. The pneumatic actuators uses compressed air with computer control mechanism and is able to produce force, position, texture, and stiffness in the form of kinesthetic and tactile feedback through the end-effector. While pneumatic power has traditionally been explored in the automation industry, haptic researchers have also explored pneumatic techniques due to their advantages over other haptic actuation methods. One of the most significant advantages is that a large pressure force can be concentrated onto a relatively small area; thus, a pneumatic actuator can easily be embedded inside an object, which makes it a reasonable alternative for mixed medical simulators.

This paper aims to provide guidelines for developing a haptic-enabled medical simulator based on pneumatics. The sections are structured as follows: Section II presents the collective conceptual architecture for medical haptic systems, providing the systematic guidelines for developing any pneumatic haptic system. Section III describes the current state-of-the-art pneumatic haptic medical systems and simulators, including various categories, for example, pneumatic haptic medical palpation, minimally invasive surgery (MIS), and rehabilitation, in addition to other research that utilizes the pneumatic approach and can be used for medical purposes. The study of various technical aspects related to the design and development of pneumatic haptic medical applications is described in Section IV. Section V provides evidence regarding the performance evaluation and validation of medical systems. Finally, Section VI concludes the paper and offers some remarks.

II. CONCEPTUAL DESIGN ARCHITECTURE

The fundamental concept of pneumatics is the study of pressurized air and other gases at rest and/or in motion and the

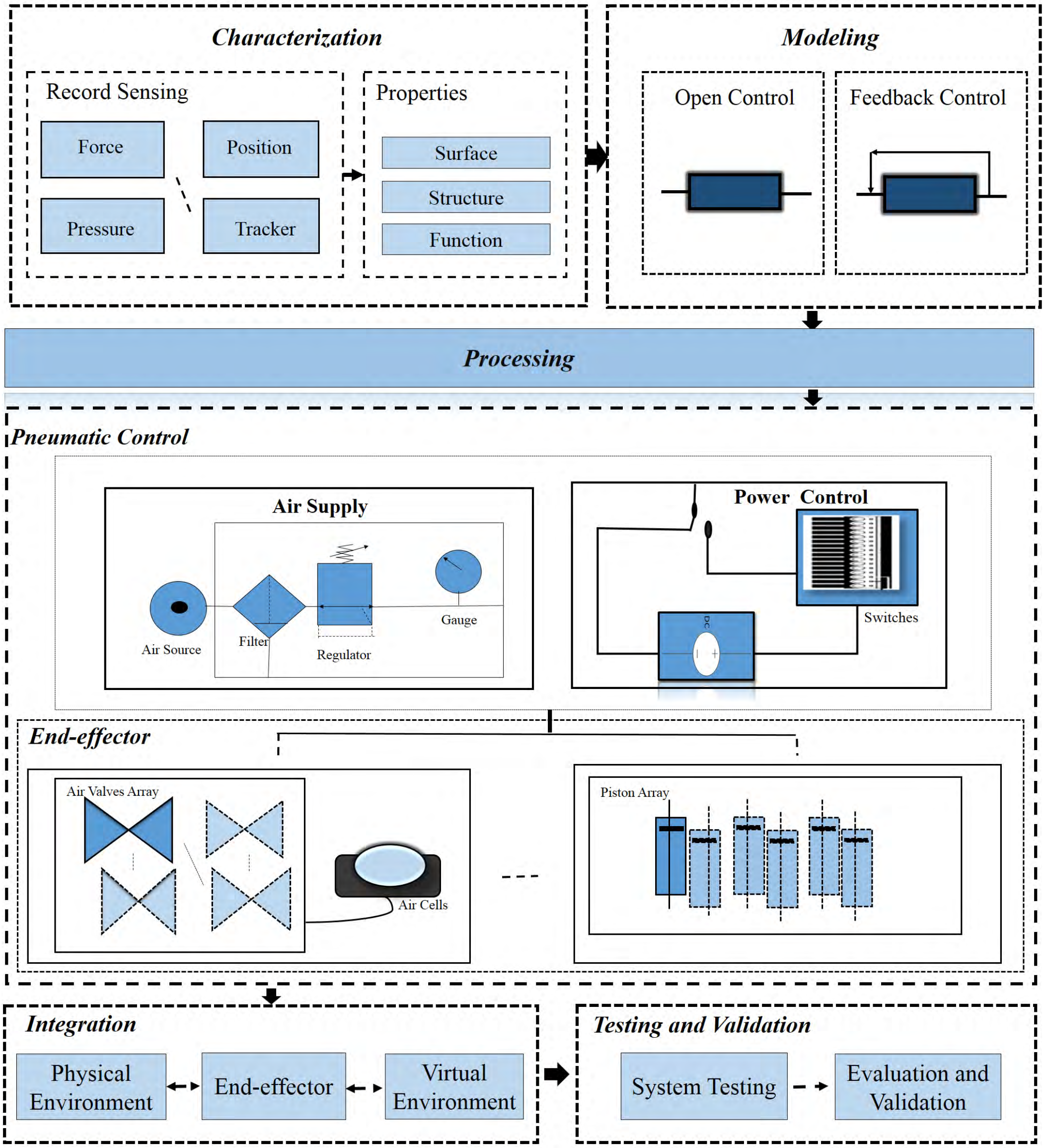

FIGURE 2. General conceptual design architecture for the pneumatic haptic systems.

application of that knowledge in the design and control of machines [13]. In a pneumatic system, energy is stored in the potential state under compressed air working energy (kinesthetic energy and pressure), which allows the compressed air to expand [14]. The effect of the expanded air is responsible for the key factors of tactile and kinesthetic haptic feedback.

While pneumatic actuation is conventionally used in industrial automation and robotics, it also has medical applications [15], [16], [17]. Haptics researchers have utilized the following benefits of pneumatics to overcome the limitations of commercial haptic devices:

1) Low cost and quick response [18], [19]
2) Lightweight apparatus [20]
3) No restrictions on output size and shape [21]
4) No return lines, in contrast to a hydraulic system [19]
5) Easy control of speed and pressure [19]
6) Suitable for a clean environment [22]
7) High power-to-weight ratio [21]
8) Safe to use [23].

Utilizing these benefits, many researchers have used pneumatic techniques in the haptics domain. However, due to some limitations of pneumatic actuators (discussed in section. IV. B.) the development of a pneumatic haptic system requires a systematic development procedure. Therefore, this section introduces a general conceptual design architecture combined with development life cycle guidelines specialized for pneumatic actuation in a haptic system. To the best of our knowledge, this is the first attempt to generalize the development life cycle in the form of a conceptual design architecture. However, the development life cycle for only a pneumatic system was introduced in [24]. The proposed conceptual architecture is shown in Figure 2.

The development process of a pneumatic haptic system (PHS) combines multiple disciplines to obtain the final results. For example, the system consists of pneumatics, mechatronics, software, computers, and haptics disciplines. Because of the involvement of multidisciplinary domains, certain strategic steps must be followed, such as i) analysis and characterization of the conventional system, ii) system design and fabrication, and iii) testing and evaluation. The following subsections explain the conceptual architecture, specifically the key steps to developing a PHS.

A. CHARACTERIZATION STEP

The life cycle of a pneumatic haptic system begins with an analysis of the characteristics of feedback that includes the feedback types and ranges, human performance corresponding to perception, exploratory procedures involved in the interaction [25] and many others. This analysis enables quantifying the tactile and kinesthetic parameters and, consequently, the characterization of natural human spatial and tactile intuition. To this end, the characterization unit contains sensors, such as force, position, pressure, and acceleration sensors, to record every detail of the kinesthetic and tactile parameters. These quantized parameters will help to achieve a system with high fidelity and realism.

B. MODELING AND CONTROL STEP

Two traditional control approaches can also be applied to the pneumatic control. Conceptually, two kinds of control are available: open-loop control and closed-loop control [26]. The nonlinear property of pneumatic flow makes building control dynamics models a somewhat difficult task, but the selection of precise and advanced assembly offers the potential to achieve a mathematical model [27]. Closed-loop control tends to have more freedom regarding this aspect and can thus provide relatively accurate control. However, it requires real-time sensing of the resultant feedback, e.g., real-time stiffness sensing, which is sometimes unfeasible.

C. PROCESSING STEP

In general, the desired output of a pneumatic haptic system is in the form of force, shape, stiffness, and position feedback achieved via airflow through the pneumatic components. Specifically, the control valves, pneumatic cylinders, and pistons are responsible for synthesizing kinesthetic and tactile feedback at the end effectors. These pneumatic mechanisms are controlled by the processor unit, which commonly consists of a computer, microprocessor, or microcontroller.

D. PNEUMATIC CONTROL STEP

1) AIR SUPPLY AND CONTROL

The standard pneumatic system consists of active and passive components. The active components include a compressor, an air tank, transmission lines, hoses, and valves, while the passive components include a pneumatic cylinder, service unit, filter lubricator, and regulator (FLR). The power control unit contains data acquisition (DAQ) or microcontroller with various combinations of relays or switches.

2) END EFFECTORS

Another core consideration for a pneumatic haptic system is the end effectors, also known as the interface, through which the actual haptic effects can be felt. The pneumatic haptic interface is highly determined by the mechanism that is used to control it. In general, the desired output of a pneumatic system is in the form of position, force, movement, and displacement feedback achieved via the airflow through the control valves. Some researchers use pneumatic components (such as valves and control regulators) to produce haptic feedback for use in air chambers that are usually made up of silicone. In fact, a membrane can be made small enough to install it in or on a device to produce force feedback to deliver the perception of stimuli at a finger pad [28]–[30]. In this type of system, the pneumatic assembly is placed in a position such that haptic feedback is produced at the interface.

Another mechanism is the manipulator, which usually uses a pneumatic cylinder (piston) to perform an actuation. The size, shape, and force response of the piston are the important factors for designing this type of end effector. The pneumatic cylinder needs to be arranged in the desired assembly, e.g., a parallel assembly used for a mechanical part to achieve the desired kinesthetic results to display the compliance property of lumps [31]. In the system, pneumatic components are involved in bodily movement to produce the haptic feedback on the interface.

In every kind of pneumatic haptic interface, the logical use of a pneumatic assembly is necessary. The variables of an assembly are the numbers of valves and cylinders arranged in series or in parallel, depending on the end effector output response. Another variable is the basic pneumatic logic used. The OR logic is used when pressure is required on a single end, while AND logic is used for pressure on both ends. Furthermore, the identification of the end effector material property is an important stage of the end effector making process. The fabrication of encounter-type end effectors plays a crucial role, as the end effector is the component with which an actual user will interact. Although the assembly of components is the key aspect for all kinds of end effectors.

In the literature, many encounter-type end effectors are made from soft materials for this purpose [32]–[34]. The fabrication of end effectors can be iterated until they are perceived as being realistic and the desired outcome is achieved. At this stage, the initial prototype of the end effector and control is attained.

E. INTEGRATION, TESTING, AND VALIDATION STEP

The discussed end effector can be used alone or integrated with the physical/virtual environment to augment the effects in the simulation, followed by testing, which is responsible for making the system curative. Therefore, it is necessary to follow the guidelines for testing the hardware and software system [35]. Many corrections will help to improve the system. The next stage is to evaluate the system based on the parameters that are analyzed in the first stage of the life cycle. The testing and performance evaluation stage will provide the initial working system. However, upgrading the system can be an iterative process over the entire system development life cycle.

System engineers need to develop a skill for design and evaluation to improve a pneumatic based haptic system. Conceptual architecture steps may provide the adequate approach to design and develop the pneumatic based haptic systems while realism and fidelity get preserved.

III. PNEUMATIC HAPTIC MEDICAL SYSTEMS

In this section, we review the existing pneumatic systems used in the medical domain and examine how they are used to construct a mixed simulation. Also, we discuss the systematic application-based taxonomy of pneumatic haptic medical systems, including skin palpation, MIS, rehabilitation, and different applications.

A. SKIN PALPATION

The skin is the largest organ of the human body. Doctors diagnose many diseases by examining the properties of a patient's skin, with palpation being the principle property used to develop a clinical diagnosis. It is used to diagnose and treat somatic problems and to evaluate the results of treatment by examining specific tissue characteristics such as inflation and stiffness of the skin. Regarding palpation, medical professionals identify the affected tissues and utilize different evaluation tests for further clarification of injured structures. A comprehensive understanding of the significance of palpation can enhance the evaluation skills of medical students [36], which illustrates the importance of haptic effects in palpation.

Different palpation techniques are commonly used in medical science, including single (index) finger and multi-finger palpation. For example, index finger palpation is used in the analysis of prostate tumor abnormalities [15], [33]. Multi-finger palpation is used to analyze abnormalities within the abdomen, breast, neck, colon, back, knee, and leg.

This section categorizes the medical haptic palpation systems into two different types: (i) palpation systems with electrical motor-based haptic devices and (ii) pneumatic haptic palpation simulators.

1) PALPATION SYSTEMS WITH ELECTRICAL MOTOR-BASED HAPTIC DEVICES

In the literature, several virtual palpation simulators that use traditional haptic devices have been reported. The first virtual palpation simulator was a knee palpation simulator that used the Rutgers Master force feedback interface [37]. Various palpation systems using commercial haptic devices are listed in Table 1. Also, Ribeiro *et al.* presented an extensive review of the palpation simulation, identifying the palpation procedure, categorization of techniques, and approaches used in systems with haptic feedback [38].

TABLE 1. Palpation systems that use the haptic device.

Electrical Motor-based Haptic Device	Medical System
Phantom Arm	Prostate cancer palpation [39]
Lab-made haptic device	Cardiac muscle palpation [40]
Phantom 3.0	Virtual haptic back [41]
Phantom Desktop	Head and neck [42]
Falcon	Femoral artery [43]
Omni	Brachial pulse [44], arterial pulse [45]
Phantom Premium	Breast palpation [46]
Phantom Premium 1.5	Rectal palpation for cow [47], breast palpation simulation [48]
Two Premium 1.5	Feline abdominal palpation [49]

2) PNEUMATIC HAPTIC MEDICAL PALPATION

Multi-finger palpation is more common than single finger palpation in medical practice. Pneumatic simulators are frequently used for multi-finger palpation since the end effector can be easily miniaturized to fit multiple fingers or a bladder-like end effector can cover multiple contacts simultaneously. Examples are summarized in Table 2.

The first example is an abdominal and intestinal palpation system [50] based on fuzzy controllers, which was further extended in [51], where a silicone sphygmomanometer bladder is used in the haptic interfaces. Similarly, multi-finger inflatable palpation actuators have been used to provide haptic feedback by using a controllable air supply and varying the internal pressure of an air balloon to re-form the distortion of digits over fingers, simulating soft tissue stiffness during palpation [52]. This inflatable actuator is made of a rubber film (SILEX ltd., HT6240; 0.25 mm thick) and has different levels of air pressure; higher air pressure represents tissues with high stiffness, while lower air pressure reflects tissues with low stiffness. In this system, air pressure is controlled by a pressure regulator using DAQ.

Li *et al.* [34] introduced the concept of granular jamming by extending their pneumatic multi-finger haptic palpation system in [9] and [52] to stiffness feedback and tumor localization [53]. Granular jamming describes the ability of granular materials to transform from an unjammed (deformable) state into a jammed (solid) state [60]; this solid state provides stiffness. The different levels of stiffness can be achieved by varying the air pressure within the chamber. The effects

TABLE 2. **Pneumatic haptic medical palpation system.**

System	Procedure	Reference(s)
Multi-finger abdominal and intestinal palpation	Uses fuzzy controllers with microcontrollers to simulate abdominal forces. A silicone sphygmomanometer bladder is used as the haptic interface. Thus, it simulates the abdominal forces in haptic interactions.	[50] [51]
Multi-finger palpation	Simulates soft tissue stiffness during palpation by varying the internal pressure of an air balloon, and re-forms the distortion of digits over fingers. The actuator is made from rubber film (SILEX ltd., HT6240; 0.25 mm thick).	[9] [52]
Tumor localization system	Granular jamming is used with the pneumatic multi-finger haptic palpation system. Also simulates tissue palpation procedures.	[34] [53]
Lump display	An air-jet with an adjustable aperture that uses pneumatic pressure to achieve different lump sizes and stiffness levels. System is capable of changing both the size and pressure at the output.	[54]
Skin display	A prototype for deformable geometry and variable stiffness is presented. Different air pressure sequences and vacuum levels allow regions of the surface to display small rigid lumps and different combinations of lump sizes and stiffnesses. Stiffness is demonstrated using the particle jamming technique.	[32] [55] [56]
Index finger prostate (DRE) palpation	Prototype of seven-cell augmented haptic prostate palpation simulator, designed and fabricated with the end effector in a layered architecture and using pneumatics and particle jamming techniques. Particles are embedded within the balloon inside each membrane.	[33]
Human tissue behavior simulator	To mimic human tissue behavior, two control laws are introduced: impedance control and back-stepping control with a closed-loop stiffness. For the pneumatic actuation, an Airpel cylinder is used.	[57]
Palpation simulator	Using a parallel link mechanism, a pneumatic parallel manipulator is developed as a compact display device with multiple DOF. Provides minute force feedback using air compressibility.	[58]
Breast palpation simulator	Uses pneumatic parallel manipulator, including a 3D breast model that is attached to an upper plate.	[59] [31]

of jamming (solidify) and unjamming (liquefy) are used for skin locomotion. The membrane plays a significant role in the granular jamming, being used to achieve a specific stiffness [61].

Gwilliam *et al.* [54] proposed a lump display for an air-jet with an adjustable aperture that uses pneumatic pressure to achieve different lump sizes and stiffness levels. Stanley *et al.* [32] demonstrated a prototype for deformable geometry and variable stiffness, which was achieved using a distinct sequence of air pressure and vacuum levels that allows regions of the surface to display small rigid lumps and different combinations of lump sizes and stiffnesses. To demonstrate the effect of rigid cells (stiffness), the authors used particle jamming. Particle jamming is also known as granular jamming. Stanley A. et al. extended their work to the adjustable material mechanical properties of a jamming haptic interface in [55]. Particularly, the shape is controlled by a commanded open loop. Therefore, the author further extended the work in [56] and reported closed-loop shape control of a haptic jamming surface, using a 3 × 4 cell prototype with the Kinect depth sensor for feedback control. The prototype may provide promising results, demonstrating the numerous types of tissue interactions in medicine.

Talhan and Jeon [33] demonstrated the seven-cell prototype of an augmented haptic prostate palpation simulator. The authors designed and fabricated the end effector in a layered manner and used pneumatics and particle jamming techniques, with particles embedded within the balloon inside each membrane. Therefore, the end effector is capable of changing its shape, size, and stiffness systematically to augment the effects of various prostate abnormalities within the single end effector. The abnormality's effects range from a single, small, deep tumor to multiple, larger, stiff tumors. The silicone prostate end effector is situated within the customized male lower body human torso to augment the realism.

Recently, Herzig *et al.* [57] presented a medical haptic simulation to mimic human tissue behavior. Pneumatic actuation (via an Airpel cylinder) is used, because of its low friction, to simulate the contact of a surgical tool with human tissues


(a) (b)

FIGURE 3. Illustration of pneumatic parallel manipulator [31]. (a) Pnuematic Parallel Manipulator. (b) Developed Palpation Simulator.

or organs. Two controller laws are suggested, with an electro-pneumatic actuator cast used as a haptic interface.

Pneumatics also provides a mechanism for building a manipulator for haptic feedback. Takaiwa and Noritsugu [58] developed a pneumatic parallel manipulator as a compact display device with multiple DOF using a parallel link mechanism. It provides the capability of low force feedback using air compressibility. This work was applied to breast palpation simulators, including a 3D breast model attached to an upper plate of a pneumatic parallel manipulator [31], [59], as shown in Figure 3.

B. MINIMALLY INVASIVE SURGERY (MIS)

MIS, or laparoscopy, is a revolutionary medical surgery technique that enables faster recovery and less scarring than traditional surgery. MIS plays a vital role in residency training in different surgical disciplines, such as general, pediatric, thoracic, oncology, and colorectal surgery. MIS requires an entirely different skill set because of the limitations of tactile sensation and the distance separating a surgeon's hand from the target organ. Therefore, professional training is necessary for medical practitioners [62]. The haptic feedback in MIS was proven to improve the skills of surgeons in [63] and [64].

Pneumatics has contributed to the production of haptic feedback in MIS systems. The evidence is listed below, proving that haptic feedback generated via pneumatic techniques is effective for a real MIS experience. Table 3 summarizes the MIS systems that have taken pneumatic haptic feedback into account.

An early attempt to use pneumatic actuators to deliver tactile feedback to an operator's hand in a teleporting environment is presented in [65]. The display makes it possible for an operator's hand to perceive the distinguished patterns, forces, and displacements. The prototype design consists of a 5×5 tactile display of pneumatically actuated pins, controlled using pulse-width modulated solenoid valves. The pneumatic actuators and a mix of conventional and micromachining techniques are used. The display was characterized as a linear system, and the ability of human subjects to discriminate patterns, forces, and displacement was measured. As a result, the displacements that were detected by human subjects were as low as 0.1 mm.

Other early attempts involving the use of pneumatic pressure for MIS application are presented in [66] and [67]. In these studies, the authors simulated the rheological properties of surgical tissues by using a single tactile-kinesthetic element device, which comprises a linear concentric cylinder (like a telescope) connected to the pneumatic servo valve. The pressure of the device is controlled via a servo valve that supplies a suitable pressure to increase the contact area of the finger with increasing palpation force.

Another study was performed to prove the importance of the combined effect of tactile and kinesthetic feedback in MIS [68]. The authors used a pneumatic-actuated balloon-based tactile display mounted on a commercial haptic device (PHANToM premium 1.0) for the master system. The 3-axis tactile display provides normal and shear forces to the fingers using hemispherical latex balloons. The authors further evaluated the effects of adding tactile, kinesthetic, and combined tactile/kinesthetic feedback via a psychophysical experiment. Consequently, the study proved that combining haptic feedback for an MIS is efficient and improves the accuracy of expert surgeons. Also, a recent review by Enayati et al. provided the objectives and challenges of organizing haptic technologies in robot-assisted surgeries like MIS [69].

Master-slave robotic-assisted surgery via a telerobotic system is another way to perform MIS. It allows a surgeon to perform surgery by sensing the affected region of the patient's body. The system consists of a slave (remote) robot and a master (local) robot. The master is handled by a human operator, who controls the slave environment via contact forces. In this telerobotics environment, haptic feedback becomes more important.

One example considered the fact that the inclusion of cutaneous and kinesthetic feedback provides the sense of the position, force, and movement of the robotic end effector, which is relative to tissues within the body and enables the surgeon to feel tissue characteristics, to feel the appropriate tension of sutures, and to identify pathologic conditions [70]. In general, the forces applied to surgical tools are typically in the range of 0 to 5 N [29]. Under this observation, Wottawa *et al.* [30] demonstrated the forces on the tools via a pneumatic simulation with 3×2 arrays of silicone balloons. The pneumatic actuators were mounted onto the da Vinci robotic grasping tool shown in Figure 4. The structure of the system includes a polydimethylsiloxane surface as the actuator membrane and a compact pneumatic control system. They designed the actuators, with a size $1.0\,cm \times 1.8\,cm \times 0.4\,cm$, such that they could be attached to the da Vinci system's grasper [71]. The balloon actuators are in contact with the thumb and index finger. Whenever the balloon expands, it provides upward force feedback to the fingers of the operator. This work further applied a similar technique by offering five different levels of force feedback via actuators to the fingers [30]. Piezoresistive force sensors are used to measure these forces.

Shimoga [73] described three different methods for providing pneumatic stimuli to the user: 1) a single air-jet fired toward the skin to indicate contact, 2) an array of air-jets fired toward skin to increase the resolution, and 3) an array of air-jets fired with different patterns. Shimoga and Khosla [74]

TABLE 3. **MIS pneumatic haptic systems.**

Study	Procedure	Reference(s)
Tactile feedback display for teleoperation	5×5 tactile display of pneumatically actuated pins, controlled using PWM solenoid valves. Enables human subjects to discriminate patterns, forces, and displacements.	[65]
MIS prototype haptic application	Simulates the rheological properties of surgical tissues using a single tactile kinesthetic element device. A linear concentric cylinder (like a telescope) is connected to a pneumatic servo valve.	[67] [75]
MIS haptic system	3×2 pneumatic actuator array mounted onto a da Vinci robotic grasping tool. The actuators are in contact with the thumb and index finger. Therefore, when actuators activate, upward force feedback is sent to the operator's fingers.	[70] [29] [72] [71]
MIS telerobotic force reflection system	A glove-like hand interface is used to reflect touch and force in telepresence MIS. Pneumatic tubes are used to allow the remote robot fingers to apply force.	[74]
Master-slave forceps manipulator	Pneumatic cylinders are used as actuators for telepresence surgery. The force feedback is achieved using a multi-DoF forceps manipulator. The forceps manipulator is driven by pneumatic cylinders, which are used as the actuators.	[76] [77] [78] [79]
Pneumatic teleoperation system	A hybrid control law is applied to a system driven by solenoid valves, which are used as actuators. Low-cost solenoid valves are used at five discrete control levels, and sliding-mode control of the actuators is performed to reduce the switching activities of the valves and improve the dynamic performance of the actuators.	[80] [81] [82]
Lightweight forceps manipulator	The power of PAMs is used to develop the perception of force in the forceps manipulator. The system allows the perception of force using a lightweight, compact system without the use of a force sensor.	[83]
Pneumatically driven robotic forceps	The flexible wrist forceps concept suggests using a pneumatic cylinder with a push-pull motion to drive the system. The control performance is considered acceptable for intuitive manipulations using a master-slave system.	[84]
Master-slave teleoperation system	A pneumatically actuated master robot (haptic device) is made with a pneumatic cylinder and with strain gauge-based force sensing configured to operate the slave from a scanner room during imaging.	[85]

also contributed to telepresence MIS by introducing a glove-like hand interface. This glove interface interacts with the remote surgery environment to reflect touch and force. This force reflection system involves a set of flexible pneumatic tubes that are attached to the human fingers to reflect the grasping forces of the remote robot fingers.

Another interesting work involves a pneumatically actuated master-slave teleportation system, which includes a pneumatic haptic display (master robot) designed for MRI-guided telesurgery [85]. The master with a strain gauge is configured to operate the slave in a scanner room during imaging. The slave robot follows the insertion motion of the master, while the haptic device applies the needle insertion force as measured by the force sensor. The master device designed with a pneumatic cylinder also achieves successful teleportation tracking.

Kawashima *et al.* [76], Tadano and Kawashima [77], and Kim [78] developed a master-slave system with multi-DOF forceps manipulators. In the system, force feedback is achieved using a forceps manipulator by utilizing pneumatic cylinders as actuators, as shown in Figure 5. A similar system was proposed in [80] with a hybrid control law for a pneumatic teleoperation system using solenoid valves. The system uses low-cost solenoid valves at five discrete control levels and uses sliding-mode control pneumatic actuators to reduce the switching activities of the valves and improve the dynamic performance of the actuators [81], [82].

Another pneumatic technique, i.e., pneumatic artificial muscles (PAMs), is used for MIS haptic medical systems.

FIGURE 4. **Illustration of pneumatic actuators mounted on the da Vinci robotic grasping tool introduced in [29], [70], and [72].**

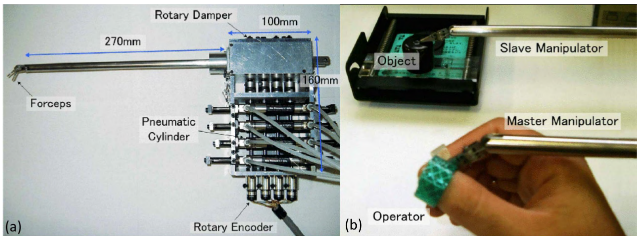

FIGURE 5. **Illustrations of master-slave manipulator and forceps manipulator for telepresence surgery (a) Master-slave Manipulator (b) Forceps Manipulator [77].**

PAMs consist of flexible and inflatable membranes that exhibit behaviors similar to orthotropic material and are operated using pressurized air. PAMs possess an expandable membrane that can be expanded and contracted using pressured air [86]. A slave system [83] was considered to investigate the applicability of PAMs to MIS. The system allows the perception of manipulation of forces using PAMs. To validate the concept, the author performed a comparative study of forceps driven by pneumatic cylinders and PAMs to confirm haptic feedback. Although the system provides haptic feedback to the operators, it decreases stability. Another example is simplified flexible wrist forceps driven by a pneumatic cylinder with a push-pull motion, which are easy to fabricate, reducing manufacturing costs and future miniaturization [84]. The control performance is considered as acceptable for intuitive manipulations using a master-slave system.

C. REHABILITATION

Rehabilitation is a specialized health care method that is performed to improve, maintain, and restore physical strength, perception, and mobility, with definitive results. It helps people to gain greater independence after undergoing an illness, an injury, and/or surgery.

The importance of haptic feedback for physical rehabilitation was recognized and described by Burdea [87]. A pneumatic system helps affected people during rehabilitation in the form of augmented haptic sensation. One telerehabilitation system is a PC-based orthopedic system that was developed to monitor patients at home from a clinic remotely; it was also developed to enhance patient safety [88]. This system contains an RMH-II hand master, which is operated at 80 psi of air pressure via software control. The work of [88] was applied to develop a force feedback glove with a new design [89]. It has four custom pneumatic actuators arranged inside the palm. The wires, pneumatic tubes, and actuators provide significant force feedback (up to 16 N) to each finger in the direction of flexion and extension. Also, a prototype of the Rutgers ankle device was presented in [90], who used the method of haptic feedback to enhance the interaction realism. In this system, the pneumatic actuators are used to provide a change in stiffness.

Hand rehabilitation and a human grasper were proposed in a study of the pneumatic tactile display [91]. The haptic display mechanism was designed for three fingers, including the index finger, middle finger, and thumb, to enable the perception of different stiffnesses at the contact points autonomously and controllably. The three digits are appropriately adjustable to match the inner pressure of the haptic display device.

Takiwa et al. used a pneumatic parallel manipulator and developed a mechanical device to support human rehabilitation wrist motions [59]. The manipulator is similar to the pneumatic parallel manipulator shown in Figure 3 (a), except it also includes a palm gripper. The pneumatic actuators provide minute force control due to the air compressibility. The system supports multiple degrees of freedom even for complex wrist motions. Another application of force-feedback systems is the bilateral teleportation system proposed in [92]. This self-sensing bilateral teleportation system operates using a 1-DoF pneumatic manipulator. Although the authors did not directly mention the usage of the system, the possible utilization of this simple design as the control unit of a master-slave system may be useful for medical rehabilitation systems.

The literature presents evidence that pneumatic actuators can be used for lower limb prostheses. For instance, a prototype was proposed to augment the sensory information for haptic feedback system lower-limb prostheses [93], [94]. Four pneumatically actuated silicone balloons were worn around the residual limb to perceive the sensory feedback. The human perceptual test results suggest that the use of pneumatic haptic feedback is a reliable method for providing sensory feedback for lower limbs, but the prototype was tested on normal subjects. In addition, a recent study provided evidence that pneumatic haptic feedback offers significant improvement in system controls under a perceptually devoid environment [95]. The study compared prototypes with a

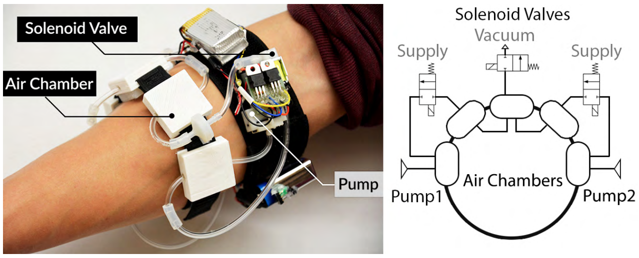

FIGURE 6. Arm-worn haptic interface [103].

vibrotactile array and with pneumatic actuated arrays for haptic feedback in lower-limb prostheses. However, desensitization occurred for one of the participants. The possibility of this behavior may be due to the design of the silicone support in the prototype.

PAMs also play a major role in rehabilitation systems because they have a unique power-to-weight ratio. PAMs also possess unique characteristics, such as flexibility, which makes them ideal for human rehabilitation applications. Therefore, PAMs have great potential as resources of resistance for strength training and recovery [96]. Based on the strengths of PAMs, Hall et al. developed an isokinetic exercise system [97]. The system uses simulated neuromuscular actuators to maintain a low velocity during concentric and eccentric knee movements.

Many rehabilitation systems that operate based on the pneumatic principle are available. However, their haptic feedback and realism have not been reported. Therefore, they are considered as out of the scope of this paper.

D. MISCELLANEOUS

This section presents various pneumatic haptic medical simulators that do not fit into the previously covered categories. It also discusses some other pneumatic haptic systems that could be applied to the medical domain. Table 4 summarizes these other pneumatic systems that can be used for medical haptic feedback.

Silveira *et al.* [98] proposed a BirthSIM model for developing a haptic interface for a childbirth simulator. The authors extended their work in [99] to increase the biofidelity of movement and forces during fetal descent. The BirthSIM model provides two degrees of freedom and pneumatically actuated interaction with synthesized effects generated during the back-stepping baby delivery procedure. The achieved control is used to obtain the targeted trajectories of end effectors and the stiffness rendered at the end effectors [100], [101].

Another haptic system called the air-pillow telephone was proposed by Iwaki *et al.* [102]. The system allows individuals separated by physical distance to mutually experience one another's touch. The application is beneficial to those suffering from loneliness and depression. Another haptic interpersonal communication system, called PneuHaptic, involves a pneumatically actuated haptic interface that can be worn on the arm [103], as shown in Figure 6. The system triggers a range of tactile sensations in the arm by alternately pressurizing and depressurizing a series of custom molded silicone chambers.

A functional-MRI compatible haptic interface, designed with pneumatic actuation to perform sensorimotor tasks in an MR scanner, was proposed by Yu *et al.* [104]. F-MRI experiments showed that the pneumatic-actuated force display device is MR compatible and does not produce image artifacts. In addition, satisfactory force control was achieved when testing the nonlinear pneumatic system with a sliding mode controller.

Many researchers have modified commercial haptic devices successfully, using a pneumatic assembly to obtain augmented end effectors. For instance, a different haptic epidural needle insertion simulator with electro-pneumatic actuation, which was able to transmit haptic sensations to anesthesiologists while executing the epidural anesthesia procedure, was proposed in [105]. Pneumatic actuation was used with a commercial haptic device (Geomagic Touch) to reduce the 'loss of resistance' phenomenon to help physicians control the needle depth. The study proved that a pneumatic actuation can mimic the responses of a needle and fluid leakage of a syringe. Also, the electrical device supplied the needle insertion force. However, the haptic device was not sufficiently powerful to deliver the necessary rendering forces.

Kim *et al.* [106] used PHANToM with an attached pneumatic array housing to add tactile feedback to PHANToM. This work provided useful complimentary tactile information with the help of a pneumatic air-jet display. Similarly, Akbar and Jeon [107] illustrated the encounter-type haptic interface using a commercial haptic device, i.e., Omega. The system was modified with a silicone-balloon-shaped end effector to produce the impedance-type (position sensing and force control) feedback effect. The position of the balloon-shaped end effector was controlled by the closed-loop control, and the size of the balloon was controlled by blowing air into the balloon. In the same way, Usevitch *et al.* demonstrated the use of pneumatics and particle jamming in the customized Navint Falcon to provide variable sizes and stiffness values to the outer layers of the end effector, which was achieved by controlling the vacuum level and using the particle jamming technique [108].

IV. TECHNICAL ASPECTS TO CONSIDER

Realism is an integral part of a haptic system for medical simulation [109]. There are some technical aspects that must be considered in pneumatic system design to achieve realistic results. This section will explore technical aspects related to the design and development of pneumatic haptic medical applications.

A. HAPTIC PROPERTY MODELING

In any haptic system, quantifying and modeling the desired feedback are the key challenges to attaining an accurate simulation. The pneumatic haptic medical system is not an exception. The following are some examples of this property modeling carried out in the study of pneumatic haptics.

TABLE 4. Miscellaneous medical pneumatic haptic systems.

System	Purpose	Reference(s)
BirthSim childbirth simulator	To produce bio-fidelity movement, a haptic birth interface simulator was developed. Pneumatic servo valves are used to achieve the desired actuation effects.	[98] [99] [100] [101]
Air-pillow telephone	The system allows individuals separated by physical distance to mutually experience one another's presence. A pneumatic piston and cylinder are used to actuate air in the pillow.	[102]
PneuHaptic	This interpersonal communication system utilizes a pneumatically actuated haptic interface worn on the arm. The system triggers a range of tactile sensations on the arm by pressurizing and depressurizing silicone chambers.	[103]
Functional-MRI compatible haptic interface	This was developed to perform sensorimotor tasks in an MR scanner. The pneumatic-actuated force display device is MR compatible and exhibits satisfactory force control.	[104]
Haptic epidural needle insertion simulator	The system reproduces the haptic sensation felt by anesthesiologists when performing a procedure. Geomagic Touch, combined with an electro-pneumatic actuator, render needle and LOR of the syringe behavior during insertion into a biological layer.	[105]
Pneumatic tactile display	Combines the PHANToM point force haptic display with a pneumatic tactile array housing. This work provides useful realistic complimentary tactile information and a compelling virtual environment.	[106]
Encountered haptic display	A commercial haptic display (Omega) is modified with silicone balloon actuation to change the shape at the end effector to perceive position and force control.	[107]
End effector for kinesthetic haptic display	Navint Falcon is used to provide variable size and stiffness values to outer layers of the end effector. Pneumatics and particle jamming techniques are combined to yield different stiffness values.	[108]

The use of commercial sensors is necessary for quantifying parameters. These sensors need to be attached to a system where haptic stimuli are commonly exerted. For example, Cheng *et al.* [50] quantified forces to use as reference force input during actual human bladder palpation. The resistive force generated by the bladder was measured using a force transducer that was fixed at a penetration depth of 2 cm. Also, Fan *et al.* [94] quantified tactile and kinesthetic forces using conventional sensors, such as a piezoresistive force sensor (Flexiforce, Tekscan), integrated into the sole of a shoe. The ideal position of the sensor is helpful in quantifying perception.

B. PNEUMATIC SYSTEM DESIGN FACTORS

The design of the system is one of the necessary steps for achieving realistic results. Therefore, some common issues for pneumatic haptic systems are discussed below:

i) Pneumatic components should be selected according to the force requirement. The selection of a pneumatic component is directly related to the requirements, such as the device weight, output force range, system stability, and cost [21]. For example, an oversized valve for the same air supply generates more than the desired force, which may lead to a non-natural feel, and immoderate air consumption may occur due to the outsized component. Also, oversized valves have relatively high friction with stick-slip effects, which prevent smooth motion under many circumstances. Although haptic system requires low pressure and airflow as compared to the industrial applications, off-the-shelf components are the decent option. Therefore, often oversized servo-valves are used. However, selection of the component is a crucial step.

ii) The building of an analytical and mathematical model of air dynamics for pneumatic actuation is one of the most challenging tasks because of the nonlinear behavior of pneumatics [110]. The mathematical model involves three key considerations related to air dynamics: a) the air flow rate in the pneumatic components, b) the pressure, volume, and temperature of the air in the cylinder, and c) the dynamics of the load [111]. A precise pneumatic mathematical model is an important part of control design and operation optimization [112].

One of the key considerations for developing a mathematical model for pneumatic actuators is to find a component coefficient under all operative conditions. For that, the various functional characteristics and parameters must be tuned under all operative conditions [113]. Furthermore, the effects of nonlinear air flow through a valve, air compressibility and leakage between chambers, an inactive air mass at the end of the stroke, time delay and attenuation in the pneumatic lines are essential [114]. Also, the cylinder dynamics, payload motion, friction, and valve characteristics must be taken into account when estimating a nonlinear dynamic model, such as the servo pneumatic positioning system [115].

iii) One of the interests of the pneumatic haptic system is to provide passive compliance because of air compressibility, which does not require an active stiffness control and reduces the electronics control. However, the nonlinear flow using pneumatic components, low bandwidth of actuators, and non-linear behavior require a fine control mechanism. Additionally, command valves can be positioned at a significant distance due to space and design consideration, which leads to time delay and attenuations. Every pneumatic haptic medical system may require unique design and control. Thus, the bandwidth of pneumatic actuators differs in an individual system, while electric actuators must provide a 1Khz bandwidth to provide active/passive feedback.

iv) There are many types of leakages in compressed air, and they can occur in any part of a system. The common areas with leakage problems are the coupling, hoses, seals, fittings, pipe joints, one-touch fitting, FRL, condensate traps, valves, flanges, packing, and thread sealants [110]. Also, the probability of leakage increases with the volume of the system, which further decreases the force rapidity and portability [116]. Therefore, decreasing the volume of the system by minimizing the distances between the valves and actuators can help to overcome leakage. The appropriate management of leakages provides stability to a system.

C. CONTROL AND COMPUTATION STRATEGIES

Pneumatic actuators generate haptic feedback via the precise control of air pressure in an air chamber. In general, a chamber is connected to an air source, e.g., air tanks and an air compressor, using a hose and valves, and air regulators systematically control the flow of air in the chambers, the pneumatic piston [70], [81], [117], and the pneumatic cylinders [76]. For instance, electro-pneumatic pressure regulators (SMC ITV00102MMS) have been used to inflate balloon elements with a proportional air pressure of 15 psi [29], and three solenoid valves (VIA04-BW1) have been used to create a vacuum to deflate a channel [32]. In addition to the above components, fittings and filters are necessary fundamental elements of a system.

Automatic computerized systems explicitly achieve control for a pneumatic haptic system. The major controls used to produce the desired output force to generate inflation in the end effectors are the following: i) microcontroller (e.g., MicroChip, PIC 18F4550) [51], ii) DAQ (e.g., NI USB series DAQ interface) [94], [102], and iii) digital signal processor [70]. These methods are preferable due to their programmable, quick, and precise control over the hardware.

The control algorithm is vital to setting the sequence, pattern, and switching response time to regulate hardware. For instance, the computational algorithm is implemented using fuzzy control with pulse width modulation (PWM) used for solenoid valve control in abdominal palpation [50], neural networks are applied over an inner force control PID loop with servo valves in the master-slave manipulator for MIS [76]. Moreover, a backstepping control is another approach for one or two servo valves per cylinder which used in human tissue behavior simulation [57].

D. FABRICATION OF PHYSICAL MODELS FOR MIXED SIMULATION

In the mixed simulation haptic system, the physically touchable model plays a significant role in producing stimuli for the user. The feedback from this physical model should be the same as that from a real target body part. Particularly, in addition to the touchable but static part, a systematically controllable part, also known as the end effector of the pneumatic haptic system, needs to be carefully fabricated. There are two different types of this end effector: encounter-type and manipulator-type. The former replaces the surface of the target object, while the latter replaces a tool used for touching the target object. Because of this, the encounter-type end effector should be relatively more flexible to represent various haptic properties.

1) MEDIUM SELECTION

In the case of an encounter-type end effector, the haptic properties of the material used for the end effector should be very similar to those of the target surface. For instance, a thin film silicone membrane composed of SORTA-Clear 40 is used to simulate deformable organs inside a body [71]. Similarly, silicone rubber film (HT6240 by SILEX Ltd.) with a thickness of 0.25 mm and a flexible silicone layer (RTV6166 A: B = 4: 6) with a thickness of 3 mm are used to simulate the touch impression of soft tissue [52].

2) CONSTRUCTION OF END EFFECTOR

The production of end effectors is highly dependent on the shape, size, and material involved. Most of the pneumatic haptic end effectors for medical simulators are made of a soft material to produce the natural texture of deformable skin. For example, in [71], an array of balloons made of thin layered silicone film was used to cover an aluminum mold that consisted of horizontal and vertical channels for tubing allocation and air chambers, respectively. Furthermore, the field of soft robotics produces reliable results with the help of rapid and digital fabrication tools, including multi-material 3D printing, shape deposition manufacturing, and soft lithography [117].

V. PERFORMANCE EVALUATION AND VALIDATION

This paper specifically addresses pneumatic haptic medical systems. The goal of a haptic health care system is to provide a life-like experience to a user. Therefore, many systems have been evaluated via human psychophysical experiments. Also, mechanical performance evaluation is crucial for any system. Therefore, we broadly categorize the performance assessment and validation techniques into two categories: perceptual performance evaluation and mechanical performance evaluation. Also, we provide references corresponding to the different tests and techniques that have been performed to evaluate and validate pneumatic haptic systems.

A. PSYCHOPHYSICAL TEST

Psychophysics quantitatively discovers the relationship among physical stimuli, sensation, and perception. Therefore, the psychophysical test is one of the effective methods for characterizing the sensing of haptic features. For example, King *et al.* [29] developed a pressure stimuli system for the da Vinci surgical system. The authors performed psychophysical tests to quantify the effectiveness of the human sensory system. The tests were carried out to stimulate the finger mechanoreceptors and observed that pneumatic balloon-based tactile input is more efficient at providing tactile information to surgeons' fingers. In another study, a normal human was considered as the subject for pilot testing, and the result was used for lower limb amputees as the ideal position for the sensor during rehabilitation [94]. The results of the psychophysical test provide accurate sensing parameters. However, this type of examination needs to follow proper guidelines in the design of the psychophysical test [118]. Also, these tests are exhaustive.

This section provides a list of evidence of different kinds of evaluations, which were carried out for human perception evaluation.

1) FORCE AND SPATIAL RESOLUTION

Fan *et al.* [94] evaluated the force and spatial resolution of the lower-limb sensory-loss rehabilitation system by conducting a perceptual test performed on a single subject. The authors tested the prototype by providing tactile cues to the user based on plantar pressure distributions. The study described the evaluation of the force resolution via an inflation level experiment. The experiment was performed by producing all possible levels of forces against four investigated surfaces of the selected body part. The spatial perception was evaluated via a sequential actuation test and directional actuation test. In the sequential test, the subject was asked to identify the pattern of succession of activated stimuli on the feedback cuff; in the directional actuation test, the subject was asked to imitate the direction of the tactile balloon actuation. The results of studies show 90.6% accuracy during the sequential actuation and 87.5% accuracy in the directional actuation test.

2) RIGIDITY AND GEOMETRY PERCEPTION

In a haptic jamming device, stiffness and geometry are controlled via particle jamming and pneumatic actuation. Genecov *et al.* [119] performed psychophysical experiments to identify the rigidity and geometry perception of multiple participants. The stiffness was tested against a reference value and categories that were smaller and larger than the reference value. The just-noticeable difference (JND) of the stiffness and the geometry were evaluated against Weber's fraction (WF) law. The study shows the average WF for stiffness perception was 16.0% and for size perception was 14.3%.

3) STIMULI OF THE JND

An air-jet lump display was proposed to identify and localize hard lumps within soft tissue during MIS palpation. Various experiments were performed to test the lump display to study the JND stimuli [120], in which the author identified the JND of the air supply. For each orifice size, the air pressure stimuli were tested against the subject's finger pad. An analysis of the comparison stimuli of the JND was performed. Subject-averaged pressure JND values stated in the ranged from 19.4-24.7 kPa. Also, in another study, the air supply pressure and aperture size displayed a wide variety of lump-like pressure profiles; the constant stimuli method was used to determine the JND for the air pressure and aperture size. The study validated that the JND of pressure range between 19.6 and 24.4 kPag, and JND of aperture size ranged from 0.50 to 0.66 mm. The qualitative results reveal that subjects perceived a "lump-like" shape with their bare fingers [121].

4) TEST FOR LOCALIZATION

Kim *et al.* [106] developed a system that enables combining force feedback with pneumatic tactile cues. The study evaluated the pneumatic tactile display by considering multiple participants in two groups. The first group performed the localization and two-point threshold tests, and the second group performed the perception of stimulus intensity and temporal resolution tests. The authors also performed an ANOVA test to prove the significance of the data.

5) WEIGHT AND DIRECTION OF FORCE

In [122], psychophysical experiments were performed to examine the effect of the pneumatically driven haptic interface (PHI). The study evaluated the impact of an exoskeletal haptic interface on human perception capabilities. The authors performed psychophysical studies, conducting weight experiments and examining the direction of force, shape perception, and tracking curve. Regarding weight perception, the subjects compared various weights with different weight levels. Moreover, the percentage of error rate of all trials was identified for real and virtual weights. The perception of weight through the haptic interface was significantly affected by relatively low reference force levels (4.44 N, WF 5 0.5). In the direction of forces experiment, the subjects explored forces of equal magnitude but in different directions, such as from left to right and from right to left. Also, the authors analyzed the percentage of error rate in terms of the angular differences in the directions of forces.

B. MECHANICAL PERFORMANCE

The use of any system subsequently depends on its performance. Certainly, the mechanical performance makes a significant contribution to the system performance. There are three different ways to apply the physical performance measurement results.

1) TO ANALYZE THE STRUCTURAL FEASIBILITY OF SYSTEM

In a study, the feasibility of the developed actuators was proven for a multi-finger palpation system [52]. The study suggested an application for MIS, in which a surgeon palpates an organ and detects a hidden tumor in healthy tissue. In this study, the deflection response of the actuators was examined under different inflation pressures. Finite element (FE) modeling analysis was used to test the stress and deformation at the fingertip caused by palpation, while the user evaluated the performance. The computer graphics and mechanical feedback were used to recreate tissue deformation on a stiffness distribution map.

2) TO QUANTIFY THE CHARACTERISTICS OF THE SYSTEM

A validation study of the pneumatic balloon actuator was performed [71]. The system was evaluated via silicone film characterization, pressure deflection, cyclic actuation, and a fatigue test to validate the mechanical performance of the actuator design. Also, for the silicone film characterization, multiple actuators were categorized to examine the response under various combinations of inflation pressures, diameters, and thicknesses to determine the feasibility of the pneumatic balloon actuator providing tactile feedback. Furthermore, verified that the actuators are viable to provide tactile feedback for the robotic surgical system by large deflection (>2.0 mm) and a large force (>1N) while maintaining low mass (<1 g) and profile (<1 cm3).

3) TO RECOGNIZE THE SYSTEM STABILITY UNDER CERTAIN CIRCUMSTANCES

A pressure deflection test was performed to analyze the stability of the balloon actuators. A fatigue test was performed randomly over the balloon-actuation average frequency over a period of four hours [71]. An additional study, reported in [31], used pneumatics as the equidistant manipulator in breast palpation simulations. A compliance control system was constructed on a parallel manipulator to display the desired compliance with respect to the lump. This technique was used to confirm the contact point detection and display of a reference stiffness. The study demonstrated pneumatic abdominal palpation for colonoscopy by applying step input signals to achieve a good steady-state response. The authors also tested the tracking accuracy (approximated 94.2% within 300ms) of the reference input while the users were palpating the abdomen [50]. In a similar study, the authors measured the applied forces and displacement and used these measurements in the hysteresis modeling to characterize the experimental data [51]. Also, these models were used to determine the haptic force feedback necessary to simulate a body mass index (BMI) in real-time user interactions.

VI. DISCUSSION AND CONCLUSIONS

The highly desired property of a haptic medical system is to provide haptic feedback with high fidelity and realism. However, the use of physical and virtual systems does not reflect an elevated commitment to realism. Enhanced physical and augmented virtual systems are needed to overcome this limitation.

In past decades, commercial haptic devices were used in mixed-reality haptic systems, with the specific modification of HIPs playing a significant role in MRs. However, commercial haptic devices are not suitable for every application regarding point-contact-based force feedback for the haptic interface, size, cost, and workspace.

In addition to the conventional use of pneumatics with a larger force, pneumatic techniques are accessible with lower forces in a cost-effective manner. Also, the pneumatic industry offers a diverse range of electro-pneumatic components that can be used with automatic control to satisfy the desired realistic force requirements.

The force, position, texture, and stiffness feedback are key factors of any haptic system, and pneumatics can achieve these by combining different mechanical techniques, for example, particle jamming. Additionally, its cleanliness and safety make pneumatic actuation desirable in the medical domain. The miniature size of pneumatic components provides the ability to reach difficult areas for which force feedback is also desired. Furthermore, pneumatic techniques also confirm the capability of pneumatic actuation to overcome the limitations of electrical motor-based haptic devices, for instance, their cost, size, DOFs, and limited workspace.

This paper offered an extensive survey of the use of pneumatics in the medical haptic domain in various categories, including palpation, MIS, and rehabilitation. Also, other systems that can be categorized as pneumatic haptic systems and can be used in the medical domain were discussed. In addition, the paper proposed systematic guidelines for the development processes of pneumatic haptic systems by suggesting a conceptual architecture for haptic pneumatic systems, which can be used to achieve haptic effects in a system. Every pneumatic haptic medical system has unique design and control. The process of design and development of pneumatic haptic systems includes various pneumatic actuators. Typically, the pneumatic components such as servo valves, solenoid valve, and cylinder (piston) are used in the structure of the actuator to produce active/passive tactile feedback. Due to potential uniqueness in the design and control, the bandwidth of each pneumatic system may differ from the others.

In this paper, many pneumatic haptic systems were empirically analyzed. Every individual system targets various issues in the medical domain. Therefore, each particular system has been considered applicable in terms of a specific aspect. In conclusion, pneumatic systems have the potential to produce haptic feedback with realism and high fidelity. However, the current role of pneumatics in haptics needs to be further explored to enhance their capabilities in the haptics domain.

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