

Advanced User Interfaces for Teleoperated Surgical Robotic Systems

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In recent years, advances in modern technology have altered the practice of surgery from open to minimally invasive surgery (MIS) aided by robots. Teleoperated surgical robotic systems (TSRSs) provide numerous significant benefits for MIS over traditional approaches, including improved safety, more efficient and precise surgery, better cosmesis, shorter recovery time, and reduced postoperative pain. Existing TSRSs' master consoles, with improvements in vision systems, designs, and control methods, have significantly enhanced human–robot interactions, resulting in safer and more accurate medical intervention operations. Despite advances, haptic technologies, including sensors, machine assistance, and intuitive devices for user interfaces, are still limited, resulting in less effective usage of TSRSs for surgical operations. This review presents a summary of the emerging TSRSs with a focus on their user interfaces. In addition, advanced sensing, haptic, smart garments, and medical image artificial intelligence (AI) assistance technologies are shown with their potential for use in master consoles of the TSRSs are shown. Finally, a discussion on the need for a smart human-robot interface for TSRSs is given.

orifices (no skin incisions), resulting in less postoperative discomfort, shorter hospital stays, and faster patient recovery time.^[1] Despite advances, these techniques are associated with disadvantages such as the lack of sensing technologies for surgical instruments, loss of 3D vision, low flexibility, attenuation of force, and absence of haptic feedback.^[1,2] In addition, conventional MIS exposes surgeons to significant levels of radiation which is one of its most unfavorable elements.^[3]

The development of teleoperated surgical robotic systems (TSRSs), which allow surgeons to conduct surgeries across short or long distances using wired and/or wireless communications networks, has been shown to circumvent restrictions in conventional MIS. Indeed, the employment of teleoperated surgical robots has resulted in safer treatments, more efficient and accurate surgery,

better cosmesis, quicker recovery time, less postoperative discomfort for patients, and reduced radiation exposure for surgeons.^[1,4] Technically, a typical TSRS (**Figure 1**) is primarily made of a slave surgical robot consisting of one or several miniature surgical arms that can be remotely controlled by the surgeon via a master console station (user interface).^[4] The most common

1. Introduction

Modern minimally invasive operations have increasingly become fantastic alternatives to traditional open surgery. In minimally invasive surgery (MIS), surgeons can access the human body with surgical tools via one or more minor incisions or natural

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DOI: 10.1002/adsr.202200036

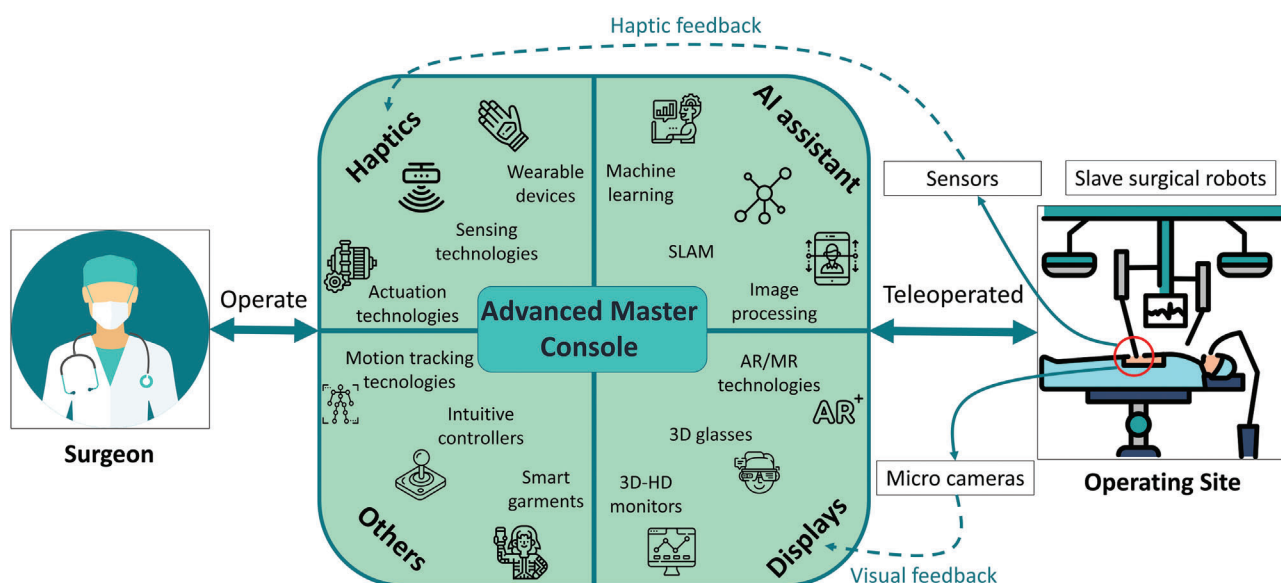


Figure 1. Schematic of the main components for a teleoperated surgical robotic system (TSRS). Acronyms: artificial intelligence (AI), simultaneous localization and area mapping (SLAM) augmented reality (AR), mixed reality (MR), and 3D-high definition (3D-HD). Credit image: Flaticon.com.

control method for teleoperated surgical robotics is a repetitive motion method that directly maps the motions of the surgeon's hand to the action of the surgical instruments.^[5] The most well-known telemanipulation system, the da Vinci system (Intuitive Surgical, Inc.) uses this control technique to directly communicate the surgeon's input motions to the articulated tip of distant surgical equipment.^[6] So far, the employment of slave surgical robots, system design, and control methods have shown appreciable advances in dexterity and precision when performing difficult surgical procedures. Whereas, most of TSRSs' master consoles can provide surgeons with essential components such as visual displays (e.g., multiple 3D-HD monitors), controllers (e.g., joysticks and panels),^[7] and other input/output devices.^[8] However, the efficacy and precision of current surgical systems are still mainly dependent on surgeon skills and experience.^[9] Therefore, one of the most pressing demands of current TSRS research trends is to modernize the master consoles, where human factors such as surgeon feelings, trust and safety, ergonomics, communication, and decision-making should be considered during the development.^[8,10] These aspects are directly related to the technologies of haptics, motion sensing, ergonomics, imaging information, and machine assistance. Yet, these technologies are still their infancy in the existing TSRSs.^[11]

First, the absence of haptics in a TSRS drives the surgeon to estimate the forces solely from visual signals, such as the deformation of tissue under stress/strain. The consequence of misinterpreting these cues is therefore likely to be ripped or damaged tissue.^[12] However, in a two-decade period, the TSRSs witnessed a slow uptake due to cost and Intuitive Surgical's patent holdings, when haptics were increasingly shown to be superfluous. As patents expire, we are seeing an increase in the number of new TSRS systems available such as the Sensus systems (Asensus Surgical Inc.), which will increase competition, lower the cost of TSRSs, and increase their use.^[13] This also prompts haptics to be

reconsidered with increasing fervor, for example, Saracino et al. recently restored haptics in the research version of the da Vinci surgical system. This study showed that haptic feedback can enhance crucial surgical outcomes for tasks that impose a cognitive burden on the surgeon, potentially in exchange for longer completion times.^[14] Similarly, numerous other studies have shown that haptic feedback has the potential to improve the effectiveness of TSRSs.^[15] However, the requirements of using suitable cost-effective, sterilizable, or disposable tiny sensors and actuators for integration into surgical instruments and rendering haptic displays respectively remain technological barriers.^[16]

Second, to ensure safety and accuracy for surgical robot remote control in TSRSs, precise motion tracking for the master consoles is important. Nonetheless, the majority of the current master consoles use mechanical components to translate the actions of the surgeons to slave robots. These translations are normally monitored by conventional motion-tracking methods such as potentiometers or encoders.^[17] However, the size of the potentiometers and/or encoders, as well as the inflexible components, can make it difficult to produce small-scale and lightweight designs or enhance the ergonomics of user interfaces. Additionally, in the context of endovascular interventional surgery (EIS), Zhao et al. stated that the use of rigid-structured user interfaces contradicts surgeons' operating habits and feelings during conventional EIS, where a surgeon always directly operates a flexible catheter.^[18] Furthermore, Wang et al. showed that although closed consoles, a common design type for user interfaces of existing TSRSs such as the da Vinci system, can provide operators with a high level of immersion, it forces surgeons to hold a fixed position during the long procedure. This not only makes it difficult for the surgeon to observe the robot and assistants, but it also puts strain on the surgeon's cervical vertebra.^[19] Open consoles, on the other hand, can be a viable option because they allow the surgeon's head complete freedom of movement, which

can potentially improve ergonomics. However, the operation of hand-eye coordination may be affected by head motion, limiting the use of open consoles in TSRSs. These issues motivate research into the development of optimal designs for the advanced master consoles of TSRSs integrated with new motion sensing methods to provide more amiable human-machine interaction.

Third, given the current challenges of haptics, motion sensing, and ergonomic designs, wearable user interfaces recently appear to be an excellent solution for improving the effectiveness of TSRSs. For example, Abdi et al. summarized that wearable devices that can deliver tactile haptic feedback on different body parts are playing an important role in teleoperated medical interventions.^[20] Compared to the common standalone force feedback devices, wearable haptic devices can also provide tactile feedback, which has a larger set of targeted surgical applications such as tissue manipulation and palpation.^[20,21] Furthermore, He et al. suggested that capturing human movements with wearable master consoles might open up new possibilities for human-machine interaction.^[22] Recently, Wang et al. introduced a unique master-slave motion alignment model that takes advantage of a wearable eye-tracking sensor and open console design to increase ergonomic and operational efficiency while overcoming the constraints of closed consoles.^[19] In the vein of wearable master consoles, robotic materials such as smart garments with sensors and actuators completely embedded in the fabric can be an excellent candidate for reducing the need for rigid components and providing a cost-effective approach.^[20,23] However, due to the inherent compliance of textiles, their maximum possible applied force is limited.^[20,24] In addition, nonlinear behavior or being susceptible to environmental effects are typical limitations when considering textile-based sensing modalities for the master consoles.^[25] Further investigation into smart textiles should be done to effectively employ them for advanced wearable user interfaces.

Finally, the advanced TSRSs are expected to give surgeons more informative data from the operating site and more autonomous and intelligent assistance. These technical needs drive research into the development of not only visual displays but also vision-sensing technologies along with artificial intelligence (AI) assistances.^[26]

The major goal of this paper is to give a thorough review of existing TSRSs highlighting their human-machine interfaces. Furthermore, it emphasizes the potential of haptic and sensing technologies as well as the promise of other technologies including smart garments, and vision sensing with AI assistance for application in an upgraded master console. The rest of this paper is arranged as follows. We first review the emerging TSRSs, including laparoscopic systems, endoscopic systems, cardiovascular surgical systems, and neurosurgical systems with a focus on the benefits and drawbacks of their user interfaces. This is followed by Section 3, where the potential of haptic technologies including sensing methods for surgical instruments, haptic actuators, and typical haptic devices for advanced master consoles of TSRSs, will be identified, respectively. Sections 4–6 will investigate potential future advancements in motion sensing, smart garments, vision sensing, and AI assistance technologies. Section 7 will explore the need for smart human-machine interfaces of TSRSs and conclude with future developments in the area.

2. Human–Machine Interfaces in Typical TSRSs

Since its introduction to medicine in the middle of the 1980s, teleoperated robotic systems have had a significant influence on many medical specialties, especially in MIS such as laparoscopic, endoscopic, catheter-based surgeries, and NOTES.^[27] A TSRS is often built on a master/slave design, with slave surgical robots coupled to the patient cart and a master console station. The surgeons utilize this station to control the slave robots that directly conduct the surgeries and get information from the operating site via visual, auditory, or haptic feedback. As a result, this step is one of the most crucial in determining the outcome of the surgical procedure.^[4,20,28] This section will re-visit the master consoles of typical TSRSs including laparoscopic surgical systems, endoscopic surgical systems, cardiovascular systems, and neurosurgical systems, with discussions on their advantages and disadvantages.

2.1. Laparoscopic Surgical Systems

For many years, the da Vinci surgical system developed by Intuitive Surgical Inc., Sunnyvale, CA, USA (FDA approval in 2000) was the only commercially available teleoperated laparoscopic system.^[29] The da Vinci surgical system employs a master/slave architecture with finger cuff telemanipulators for the surgeon's index and thumb to achieve gripping action. Its master console also contains a cushioned headrest, arm bars, variable finger loops, and an intraocular distance that can be modified dependent on the individual's demands, making it a useful tool for surgeons (Figure 2a).^[30] The immersive 3D-HD optic system and intuitive user interface return the screen location in line with the hands of the surgeon, as occurs naturally in open surgery.^[8,31] With these advancements, there has been a significant increase in da Vinci-assisted surgeries associated with better patient outcomes.^[32] However, the absence of haptic feedback and the expense, size, and complexity of the system are obstacles that have stymied the more universal adoption of this type of surgical system.^[33]

In attempts to improve the performance of the master console, many advanced TSRSs have been developed over the decades. Senhance surgical robotic system, for example, features an advanced user interface (Figure 2b) which can provide better control of the visual display during the operation. By combining an HD-3D display with an eye-tracking camera control system that centers the picture at the place where the surgeon is looking. The surgeon can adjust the display's zoom by moving their head forward or backward with respect to the monitor while pressing buttons on the grips. This innovative eye-tracking technology offers a great addition to current visualization technologies used in the TSRSs.^[34] In addition, the Senhance system also integrated a haptic interface into its master console, enabling the surgeon to handle the instruments with amplified interaction forces. In contrast to da Vinci's feedback, which mainly relies on vision rather than force feedback, the tactile force feedback from the Senhance system conveys interaction force from an instrument's distal end to the surgeon's hand,^[8] supplying a real haptic sensation to the surgeon. Sharing similar features to the da Vinci systems, the REVO-I surgical system (Meere, Gyeonggi-



Figure 2. Master consoles or user interfaces of the laparoscopic surgical systems: a) DaVinci system (Intuitive Surgical, Inc.). Reproduced with permission.^[41] Copyright 2022, Intuitive Surgical, Inc.; b) Senhance surgical system (Asensus Surgical Inc.). Adapted with permission.^[13] Copyright 201, MDPI; c) REVO-I surgical robot system (meere company). Reproduced with permission.^[42] Copyright 2021, revo; d) Avatera surgical robot system (Avateramedical GmbH). Adapted with permission.^[43] Copyright 2022, avateramedical GmbH; e) Versius surgical system (CMR surgical Ltd.). Reproduced with permission.^[44] Copyright 2022, CMR Surgical Ltd.; f) MiroSurge system. Reproduced with permission.^[26] Copyright 2021, Springer Nature; g) Enos system (Titan Medical Inc.). Reproduced with permission.^[46] Copyright 2021, Hindawi.

do, Korea) was developed for fallopian tube reconstruction, cholecystectomy, and partial nephrectomy surgeries and has been used in animals.^[35] Its user interface (Figure 2c) has a 3D image viewer, a handle, and a foot pedal unit. This master console allows the surgeon's hand motions to be sent to the robot arm through the handle, while equipped with an emergency stop button on the right side of the master console in order to prevent unmanageable mistakes and ensure patient safety.^[36] Recently, this system has been upgraded with haptic feedback and reusable instruments, which address a key gap in the da Vinci system.^[35] Similarly, while the MiroSurge's user interface is built on the same basic architecture as the da Vinci master console, including finger loops for the index and thumb manipulating end-effector movement of surgical instruments, various advancements have been made in this system. The main difference between the MiroSurge compared to the da Vinci is that it uses a commercial haptic interface—Sigma.7 haptic device (Force Dimension, S.A., Nyon, Switzerland) to transmit input motions and deliver haptic feedback to the surgeon (Figure 2f).^[37] The Sigma.7 haptic device has a three-part electromechanical structure with seven active degrees-of-freedom (DOFs) including three active translations, three active rotations, and an active grasping providing high-precision force feedback. Another advantage of the user interface of the MiroSurge is that the surgical images are shown on a video monitor right in front of the operating surgeon. The surgeon can move their head freely with this open console, however the hand-eye coordination operation based on the eye coordinate system is influenced by the head motion. The display-based master-slave motion alignment paradigm is difficult because the head and the display coordinate system do not correspond.^[19]

To assist surgeons with more flexibility and comfortability in performing MIS, the user interfaces of the Versius and Avatera surgical systems have been developed with new designs. In the Versius system, its user interface has an open console and 3D-HD vision with the use of polarized glasses and joystick handles that allow the surgeon to manipulate the system from a sitting or standing posture (Figure 2e).^[38] The user interface of the Avatera system, in contrast, enables the surgeon to view the entire field from an ergonomically designed position. In addition, it also uses loop-like grips to manipulate the instruments (Figure 2d). For simpler communication with the surgical team, a microscope-like eyepiece with integrated 3D-HD vision without engulfing the surgeon's whole head is used. The integration of haptic feedback in the user interface is an advantage of the Versius system compared with the Avatera, which is perceived by the surgeon from the handles, thereby enhancing the surgeon's tactile sensation while performing the surgical procedure.^[38] In the same vein, the Enos surgical system with a sophisticated 3D high-definition display provides a critical mix of surgical immersion and situational awareness in the operating theatre. The display is attached to the ergonomic workstation via a natural handle interface, which is meant to provide and sustain a comfortable surgical posture even during lengthy procedures. Titan created a workstation that is very transportable and has a minimal footprint (Figure 2g).^[39] Recently, a project called SMARTurg funded by the European Union's Horizon 2020 research and innovation program was designed to develop an advanced system for performing robot-assisted MIS. This system, including a novel approach to the user interface, is expected to reduce the surgeon's cognitive load related to the system's operation, shortening training



Figure 3. Master consoles or user interfaces of the endoscopic surgical systems: a) Flex Robotic System (Medrobotics Corp., Massachusetts, USA). Reproduced with permission.^[66] Copyright 2022, Springer Nature; b) NeoGuide system (NeoGuide Endoscopy System Inc., Los Gatos, CA USA). Adapted with permission.^[53] Copyright 2019, John Wiley and Sons; c) Invendoscope SC210 (Invendo Medical GmbH, Weinheim, Germany). Adapted with permission.^[67] Copyright 2021, Springer Nature; d) Aer-O-Scope system (GI View Ltd., Ramat Gan, Israel). Adapted with permission.^[53] Copyright 2019, John Wiley and Sons; e) Endotics system (ERA Endoscopy Srl, Pisa, Italy). Adapted with permission.^[53] Copyright 2019, John Wiley and Sons; f) EndoMaster EASE system (EndoMaster Pte., Ltd., Singapore). Reproduced with permission.^[68] Copyright 2017, arXiv. g) Monarch platform (Auris Surgical Robotics, Silicon Valley, CA, USA). Reproduced with permission.^[69] Copyright 2021, MDPI.; h) Ion endoluminal system (Intuitive Surgical, Inc., Sunnyvale, CA). Reproduced with permission.^[41] Copyright 2022, Intuitive Surgical, Inc.

time while also delivering accuracy, reduced procedure time, and expanded applicability. This system's user interface comprises a wearable hand exoskeleton with haptic feedback to manipulate surgical tools as well as wearable smart glasses for AR and 3D reconstruction of the operative field. It is envisaged that surgeons' labor will be reduced by enhancing ergonomics and information flow.^[40]

2.2. Endoscopic Surgical Systems

In addition to laparoscopic techniques, endoscopy and surgical methods such as endoscopic submucosal dissection (ESD)^[47] and NOTES^[48] have demonstrated many benefits such as low blood loss, no visible scars, fewer infection risks, and faster recovery. Endoscopic surgical systems have risen to the forefront of a variety of clinical contexts as a result of this paradigm shift.^[49] The most notable system in this category is the Flex Robotic System (Medrobotics Corp., MA, USA) (Figure 3a) which has been approved by the FDA for use in head and neck surgery (2015) and colonoscopy (2017).^[50] This system consists of a robotic console and a mobile cart carrying the endoscope and surgical instruments. Its user interface is placed next to the patient's bedside, composed of a touch screen, a magnified HD 2D visual display, a joystick, and a console-based controller. The surgeons are allowed to steer the flexible endoscope and surgical instrument via the joystick and the controller respectively.^[51] The tactile feedback provided by the instruments, which allows control of the force

applied to the tissue, is one of the system's most significant advantages. However, higher visualization for improved tissue discrimination and additional haptic feedback for better perception of tool-tissue interactions would be desirable in some cases.^[52]

Due to the development of sensing and computer-assisted technologies, the control of surgeons for an endoscope traveling inside a human body has been greatly improved. Interestingly, TSRs are using handheld interfaces more frequently for endoscopic approaches. The NeoGuide system (NeoGuide Endoscopy System Inc., Los Gatos, CA, USA) (Figure 3b), FDA approved in 2006, for example, uses computerized 3D mapping generated in real time, which can result in less unexpected force applied to the colon wall.^[8] This system's control station consists of a monitor that displays a real-time 3D image of the endoscope's position inside the colon to the endoscopist and an actuation controller that automatically converts the steering commands recognized by the tip and external sensors to move the endoscope in a follow-the-leader approach while negotiating colonic flexures. Thus, the traditional pressing of the endoscope against the colon wall is not necessary based on this mode of mobility.^[53] Similarly, the Invendoscope SC40 (Invendo Medical GmbH, Weinheim, Germany) is also a computer-assisted colonoscope, which has been FDA-approved and CE-marked. It has a hand-held control unit with backward and forward buttons, which is used to activate all the endoscopic and software functions.^[54] Although some tests indicated that this technology operated successfully,^[55] it has been superseded by the Invendoscope SC210 (Figure 3c), which is a component of the Invendoscopy E210 system and features a

cutting-edge hand-held electrical control interface. This interface is a joystick-based control plate that allows surgeons to deflect the tip in any direction. It may be attached to or detached from the In-vendoscope SC210 for easier operation.^[56] Analogously, the Aero-Scope system (GI View Ltd., Ramat Gan, Israel) (Figure 3d), a pneumatically propelled, self-steering, and disposable robotic colonoscope with two inflatable balloons, has a hand-held interface that is used to operate a 360° omnidirectional HD vision system. To protect the intestine from potential damage, electronic sensors are used to measure the operating pressure and assist the operators in keeping it below 54 mbar.^[57] This system has been granted the CE mark and FDA in 2016.^[58] Another noteworthy example of using hand-held interfaces is the Endotics system (ERA Endoscopy Srl, Pisa, Italy) (Figure 3e), a CE mark, and an FDA-granted pneumatically-driven robotic disposable colonoscope. Its hand-held controller and an HD monitor are used to manipulating the robotic device, which bends up to 180° in every direction with very high precision, both in step-by-step mode (e.g., digital mode) and continuous mode (e.g., analog mode), as well as electronic chromoendoscopy, via the workstation.^[54,59]

Numerous endoscopic procedures, including ESD and NOTES, call for sophisticated surgical techniques like grasping, cutting, or even suturing. Therefore, it is essential to consider not only how the surgeon and the surgical tools interact, but also how to manipulate the endoscope and instruments in tandem. The EndoMaster EASE system (EndoMaster Pte., Ltd., Singapore) (Figure 3f) is the most noteworthy system in this context, which includes a master console and a cable-driven flexible robotic slave.^[50] To conduct surgery with this system, cooperation between a surgeon and an endoscopist is required. Through the master interface, the surgeon can manipulate the slave manipulators and conduct treatment such as gripping, cutting, and suturing. Meanwhile, the endoscopist stands at the patient side to direct the endoscope to the targeted location and handle oversuction and inflation. Endoscopic vision and surgical navigation systems are supervised on digital monitors of the master console.^[60] So far, this system has not been approved for FDA or CE mark yet. Haptic feedback and precision control mechanism are the key features of this system; however, they are still needed to develop. The requirement of at least two operators to execute the surgical procedures is a considerable disadvantage of this system.^[8] Similarly, to the EndoMaster, the Anubiscope system (Karl Storz Endoskope, Tuttlingen, Germany) also needs at least two operators to perform.^[61] However, the STRAS, a robotic version of Anubiscope has been developed to act as a teleoperated modular platform to eliminate the need for a second physician. Through its master console with HD monitors and two controllers, one surgeon can do all surgical procedures with better results than the manual system Anubiscope.^[56,62]

Unlike most endoscopic surgical systems, the Auris robotic endoscopic system (ARES; Auris Surgical Robotics, Silicon Valley, CA, USA) has an ergonomically advanced user interface, which provides surgeons with an intuitive videogame-like controller for manipulating its flexible bronchoscope in three DOFs including one DOF for insertion and two DOFs for adjusting articulations. It also possesses a set of buttons, which could be used to switch motion from the scope to the outer sheath.^[63] During the procedure, images and video are transferred from the endoscope camera to an HD monitor located at the master console. This sys-

tem has been FDA granted since 2016.^[46] The MONARCH platform is the latest version (Figure 3g), which can triangulate bronchoscope location during the procedure and provide accurate positional data to physicians performing a bronchoscopy. It does this by combining three different navigation technologies of electromagnetics, optical pattern recognition, and robotic kinematic data. In contrast to this technique, another notable bronchoscope named Ion endoluminal system (Intuitive Surgical, Inc., Sunnyvale, CA) (Figure 3h) uses shape-sensing technology with a control algorithm to correct for any tip deflection from the intended position encountered through external forces.^[64] This system is made up of a master console with system monitors and a Plan-Point planning station, as well as a system cart containing surgical tools (a flexible catheter, a vision probe, and biopsy needles). By incorporating a thin slice preoperative CT scan, the surgeon can create a 3D airway tree that shows the navigation pathway to the target with defined anatomy bounds. This system was approved by the FDA in 2019.^[65]

2.3. Cardiovascular and Neurosurgical Systems

In cardiovascular and neurosurgical systems, the user interfaces often have many monitors to provide more visual information for the surgeons.^[70] For example, the user interface of the Sensei X system (Hansen medical Auris Health Inc.) (Figure 4a) is equipped with multiple monitors that provide the surgeon with a wide array of information including fluoroscopy, 3D mapping, and electrocardiogram (ECG) reading. It also has a remote joystick and buttons integrated into the master console to control the electromechanical slave or to convey the surgeon's commands. In addition, the user interface of this system also enables the surgeon to receive real-time feedback on the distal tip forces generated by its controller.^[27,71] Like the Sensei X system, the master console of the Magellan system (Hansen medical Auris Health Inc.) (Figure 4b) has multiple control screens, a master controller, and a joystick with 7-DOFs. Its user interface is a mobile workstation that is placed away from the operative field where the surgeon can freely perform different manipulation tasks such as the insertion and withdrawal of the catheter tip, multidirectional movement angulation, rotation, and torque position. However, this user interface lacks haptic feedback which is a disadvantage.^[72] Another notable example in this context is the CorPath GRX (the next generation of CorPath 200) interventional cockpit (Corindus, Inc.) (Figure 4c), which offers multiple monitors for real-time data about the patient's vitals and the actual procedural field (fluoroscopic and subtracted images) and two joysticks for device manipulation.^[70] The main benefit of the CorPath GRX user interface over the CorPath 200 interface is the addition of a second joystick to the control panel, which enables remote control of device distribution and lesion crossing. In addition, it includes a turbo button which is for faster device movement and a rotate-on-retract (RoR) function. In 2018, the FDA authorized this system.^[73]

So far, the use of TSRSs in microneurosurgery is still in its early stages, with the NeuroArm surgical system (Figure 4d) being the only system in clinical use.^[74] Its user interface has multiple displays which allow the surgeon to observe target tissue via advanced imaging methods such as computerized tomography



Figure 4. Master consoles of surgical systems: a) Sensei X robotic catheter system (Hansen medical Auris Health Inc.). Reproduced with permission.^[75] Copyright 2011, Zdravniški vestnik/Slovenian Medical Journal; b) Magellan robotic system (Hansen medical Auris Health Inc.). Reproduced with permission.^[75] Copyright 2011, Zdravniški vestnik/Slovenian Medical Journal; c) Corpath GRX system (Corindus, Inc.). Reproduced with permission.^[76] Copyright 2018, MPDI; d) NeuroArm system. Reproduced with permission.^[74] Copyright 2016, Hindawi.

(CT) or magnetic resonance imaging (MRI) during the surgeries. One of the innovative approaches of NeuroArm is the ability to provide real-time haptic feedback using an intuitive pencil-type interface, allowing the surgeon to manipulate and sense the tissue and environment while doing procedures. The NeuroArm interface design integrates some of the most important components of surgery as a result of these advancements, optimizing the outcomes received from the robotic interface.^[11] However, this system has not been FDA-approved or CE-marked yet.

2.4. Summary

Human factors, namely surgeons, have played an essential role in the development of teleoperated medical robots and will continue to play a vital role in the field's future progress. For example, the move from traditional laparoscopy to robot-assisted surgery was prompted in part by the need to improve surgeon ergonomics during the process by eliminating the fulcrum effect and offering improved vision. It is worth noting that the FDA modified its guideline paper on incorporating human factors into medical devices in 2016 to mandate usability testing to examine the impact of high-risk tasks on patients and/or other users. Numerous studies have also underlined the need for more research on the characteristics of surgeons such as sentiments, trust and safety, ergonomics, communication, and decision-making.^[11] These features are closely connected to the relevant user interface technologies in TSRs, such as haptic feedback, motion tracking, ergonomics, image information, and machine assistance. For example, force haptic feedback can significantly support surgeon feelings and decision-making in teleoperated catheter interventional practice.^[80] In short, the advanced interfaces in TSRs should therefore be designed and developed toward the surgeon's aspects.

Table 1 summarizes the master consoles of emerging TSRs in terms of design, components, and the state of sensing and haptic technology in these systems. So far, with the current master consoles of TSRs, the surgeons have been facilitated with well-designed master manipulators such as finger cuff telemanipulators in the da Vinci surgical system or joysticks in the Flex robotic system which helps the surgeon to flexibly control the surgical instruments. However, the lack of haptics in these devices is the

most difficult factor, which can lead to serious errors caused by surgeons, such as exceeding the applied force and causing organ perforation.^[81] This will be addressed by both sensor technologies in surgical instruments for gathering data on tool-tissue contact and actuation technologies in master devices for rendering sensation data. In addition, these master devices are mostly desktop devices and made of inflexible components, that require the surgeons to stay in correct and fixed posture during extended operations, which can cause discomfort and fatigue, reducing the efficacy of the operations. Another major flaw with present TSRS master consoles is the use of traditional tracking technologies like encoders and potentiometers, which likely makes it even more difficult to minimize size and improve ergonomics. So far, modern master consoles are generally well-equipped with advanced visual technologies such as the 360° omnidirectional HD vision system of the Aer-O-Scope system. The use of visual sensing with AI technologies, which have the potential to improve surgeon guidance, cues, and sensory feedback, should be exploited. The following sections will review the advanced technologies that have a great deal of potential for usage in TSRs' advanced master consoles.

3. Haptic Technologies for Advanced User Interfaces

In surgery, a high level of spatiotemporal accuracy and precision is required, which is dependent on human performance and can be improved with robot assistance.^[82] Knowing the physical properties of the tissue is crucial for surgeons to conduct safer interaction/ manipulation. For example, studies have shown that excessive grip or contact force during laparoscopy might result in tissue damage.^[83] It is obvious that the shift toward minimally invasive methods and the use of teleoperated robotic systems for surgery is associated with the deterioration or loss of natural force feedback, which dramatically lowers the surgeon's accessible information and thus results in difficult decision-making. Therefore, smart instruments can be equipped with sensing technologies to obtain important information such as the tool tip position, interaction forces, and tissue deformation. Importantly, the sensing data must be prominently rendered back to surgeons by one or more haptic interfaces with actuation technologies. As the result, surgeons can then make more reliable decisions.^[11]

Table 1. Master consoles of typical TSRSs.

Systems	Specification	Sensors for slave robots	Haptics	User interface description	Approval status
Laparoscopic systems					
Da Vinci surgical system ^[29]	General surgery	No	No	Comprises finger cuff tele-manipulators, a cushioned headrest, arm bars, an immersive 3D-HD optic system, and an intuitive user interface that returns the screen location in line with the hands of the surgeon.	FDA (2000)
Senhance surgical system ^[34]	Laparoscopic surgery	Force	Yes	Combines an HD-3D display with an eye-tracking camera control system that centers the picture at the place where the surgeon is looking. The display is adjustable by moving users' heads forward or backward concerning the monitor while pressing buttons on the grips.	FDA (2017)
REVO-I surgical system ^[77]	Laparoscopic surgery	No	Yes	Includes a 3D image viewer, a handle, a foot pedal unit, and an emergency stop button on the right side of the master console preventing unmanageable mistakes and ensuring patient safety.	Korean FDA (2017)
MiroSurge surgical system ^[37]	Laparoscopic surgery	Force/torque	Yes	Similar to the da Vinci master console, including finger loops for the index and thumb manipulating end-effector movement of surgical instruments.	Not yet
Versius surgical system ^[38]	Laparoscopic surgery	Force	Yes	Has an open console and 3D-HD vision with the use of polarized glasses and joystick handles that allow the surgeon to manipulate the system from a sitting or standing posture.	Not yet
Avatera surgical system ^[78]	Laparoscopic surgery	No	No	Uses loop-like grips to manipulate the instruments and a microscope-like eyepiece with integrated 3D-HD vision without engulfing the surgeon's whole head.	Not yet
Enos surgical system ^[79]	Single-port surgery	No	No	Composes of a 3D high-definition display providing a critical mix of surgical immersion and situational awareness in the operating theatre.	Not yet
Endoscopic systems					
Flex Robotic System ^[50]	Neck surgery (NS) and endoscopy (ENDO)	Tactile	No	Composes of a touch screen, a magnified HD 2D visual display, a joystick, and a console-based controller.	FDA: NS (2015); ENDO (2017)
NeoGuide endoscopy system ^[53]	Colonoscopy	Position	No	Has a monitor that displays a real-time 3D image of the endoscope's position inside the colon.	FDA (2009)
InvendoscopeSC210 ^[54]	Colonoscopy	No	No	Includes a cutting-edge hand-held electrical control interface to deflect the tip in any direction.	CE mark 2016; FDA 2018
Aer-O-Scope system ^[57]	Colonoscopy	Pressure	No	Involves a hand-held interface that is used to operate a 360° omni-directional HD vision system.	CE mark and FDA in 2016
Endotics system ^[54]	Colonoscopy	No	No	Consists of a hand-held controller which can manipulate the robotic device via the workstation.	CE mark (2017); FDA (2020)
EndoMaster EASE system ^[60]	ESD and NOTES	Force	Yes	Has two controllers for manipulating two end-effectors, and HD monitors.	Not yet
STRAS system ^[62]	ESD and NOTES	Force	Yes	Includes HD monitors, two instrument controllers, and one main scope controller for manipulating two end-effectors and the endoscope.	Not yet
Auris robotic endoscopy system (ARES) ^[63]	Bronchoscopy	No	No	Composes of an intuitive videogame-like controller for manipulating its flexible bronchoscope and HD monitors.	FDA (2016)
Ion endoluminal system ^[64]	Bronchoscopy	Shape	No	Has system HD monitors and a planning workstation with PlanPoint software.	FDA (2019)
Cardiovascular and neurosurgical systems					
Sensei X robotic catheter system ^[27]	Electrophysiology and endovascular surgery	No	Yes	Features multiple monitors with a wide array of information including fluoroscopy, 3D mapping, electrocardiogram (ECG) reading, a remote joystick, and navigation buttons.	FDA (2007)
CorPath GRX system ^[73]	Interventional cardiology	No	No	Offers multiple monitors for real-time information (fluoroscopic and subtracted images) and two joysticks for device manipulation, an additional joystick, and a turbo button.	FDA (2018)
NeuroArm surgical system ^[11]	Neurosurgery	Force	Yes	Includes multiple displays allowing the surgeon to observe target tissue via computerized tomography (CT) or magnetic resonance imaging (MRI) and an intuitive pencil-type controller.	Not yet

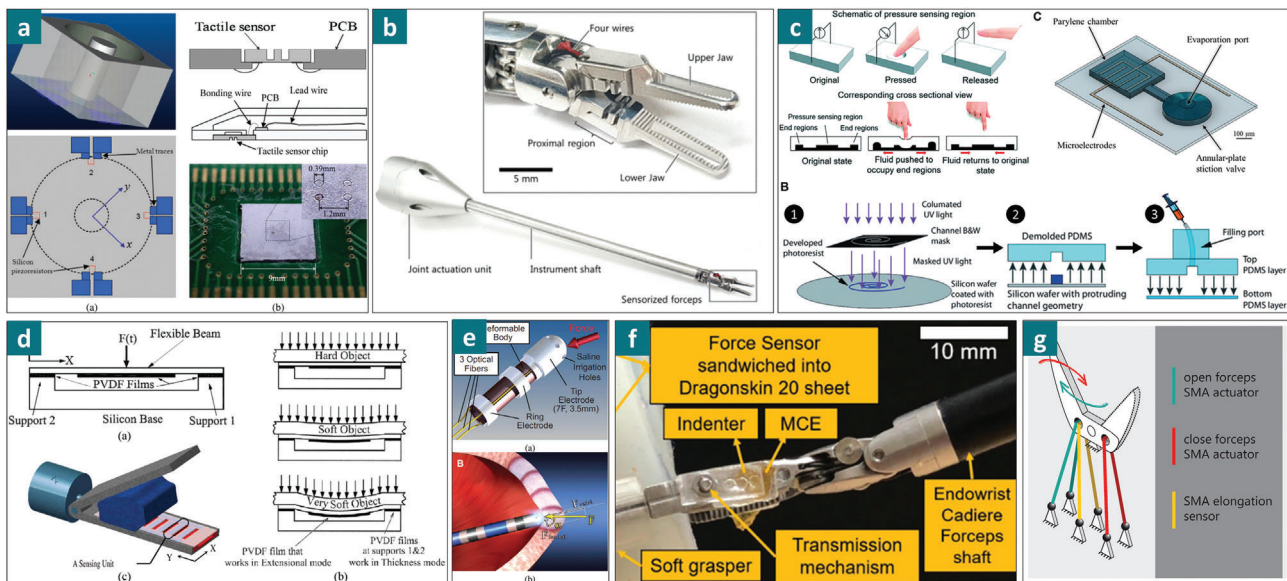


Figure 5. Examples of sensors applied for surgical instruments: a,b) Piezoresistive sensor and capacitive sensor. Reproduced with permission.^[84] Copyright 2019, IEEE.; c) Microfluidic-based sensor. Reproduced with permission.^[21] Copyright 2022, Frontiers Media; d,e) Piezoelectric sensor and optical sensor (FBG). Reproduced with permission.^[84] Copyright 2019, IEEE; f) Direct force sensing mechanochromic equipment (DFS-MCE). Reproduced with permission.^[85] Copyright 2021, Wiley-VCH; g) SMA sensor. Reproduced with permission.^[103] Copyright 2021, MDPI.

In this section, the current state of haptic technologies including sensing, actuation, and typical haptic devices with their potential obstacles to the incorporation in TSRs, as well as their potential future applications will be discussed.

3.1. Sensing Technologies for Surgical Robotic Instruments

The types of sensors used in surgical robotic instruments are heavily influenced by clinical needs. For example, suturing procedures require only force feedback, whereas tissue margin assessment necessitates multipoint tactile feedback. Given the widespread availability, the incorporation of force sensing into surgical robots has been readily achievable thus far, while tactile sensing technologies are still in the early stages of development.^[11] Although many sensing methods can produce force and tactile feedback, electrical-based sensing, pressure-based sensing, and optical-based sensing are the most commonly used technologies for surgical robotic instruments of TSRs.^[1,20,21,84]

3.1.1. Electrical-Based Sensing

The most used sensing method for surgical robotic instruments in TSRs is electrical-based sensors, which include piezoresistive, piezoelectric, and capacitive sensors.^[27,85] Based on the change of the material resistivity caused by a mechanical change in response to physical stress (e.g., compressive, shear, or thermal stress), the piezoresistive sensors can be used to produce force and tactile feedback. Strain gauges are a popular type of piezoresistive sensors, which often comprise thin, long, and zig-zag-patterned metal foils (film). Based on a deformation of the

thin film, this technology can transduce to a change of resistance. This change can be derived as follows:^[21,84–86]

$$\frac{\Delta R}{R} = (1 + 2\nu) \frac{\Delta L}{L} + \frac{\Delta \rho}{\rho} \quad (1)$$

where R , ν , L , and ρ are respectively the resistance of the piezoresistor, Poisson's ratio, length, and resistivity. This change in resistance can be expressed with respect to the applied pressure, force, temperature, or deformation. Given the accuracy and small size, strain gauges have been designed in different configurations for multi-axis force sensing. Hadi Hosseinabadi et al. present a review of 32 studies published between 2011 and 2019 that used strain gauges or commercial strain-gauge-based force sensors for force sensing of surgical instruments in MIS.^[87] In some contexts of tactile feedback, piezoresistive sensors have been chosen for their quick response, low noise in results, and ease of micro-fabrication. For example, Hu et al. developed a bioinspired 3-D tactile sensor for MIS (Figure 5a), which can exhibit a shear force sensitivity of 10.8 N^{-1} and a normal force sensitivity of 3.5 N^{-1} .^[88] So far, many researchers have developed piezoresistive hardness sensors for MIS that can distinguish between materials with significant hardness differences, making them suitable for the palpation of larger tumors.^[89] However, electromagnetic noise and temperature changes can affect this type of electrical-based sensor, resulting in inaccurate results. Furthermore, it has low sensitivity and frequently necessitates custom flexures or structural modifications to amplify local strains. Finally, this sensing type is brittle, necessitating overload protection, and will not withstand multiple sterilization cycles.^[1,87]

Capacitive sensing, on the other hand, is known as one of the most powerful means for high-resolution and compact sensor designs. This method normally uses two-facing conductive plates

with a relatively small gap made of dielectric materials in between. When an electric potential difference is applied on the plates, equal and opposite electrical charges are accumulated on both surfaces inducing a pressure to deform the dielectric layer. As a result, the distance between the two electrodes or the thickness of the dielectric layer is varied.^[1,84,87] The capacitance C for two parallel electrodes can be defined as:^[21,84]

$$C = \frac{\epsilon_0 \epsilon_r A}{d} \quad (2)$$

where A presents the perpendicular projected overlap area of the plates, $\epsilon_0 = 8.85 \times 10^{-12}$ (F m⁻¹) and ϵ_r are the vacuum and relative permittivity respectively, and d denotes the distance between two plates. Capacitive sensors work by relating changes in a capacitor's voltage to physical variables such as force, pressure, displacement, temperature, or humidity. The relationship between physical variables and voltage can be deduced using Equations (2) and (3); for example, the normal force F that changes the distance between two electrodes can be calculated as:^[21]

$$F = \frac{\epsilon AV^2}{2d^2} = \frac{CV^2}{2d} \quad (3)$$

This type of sensor is simple and easy to replicate, making it suitable for disposable use. Kim et al., for instance, proposed the use of capacitive sensors for the forceps to measure 5-DOFs force/torque (Figure 5b).^[90] Furthermore, it outperforms strain gauges in terms of stability and sensitivity in warm and wet environments.^[84] While seven state-of-the-art capacitive sensors used for force sensing were summarized by Hadi Hosseinabadi et al.,^[87] Bandari et al.^[84] compared six cutting-edge representative studies of capacitive tactile sensors. Despite the benefits, the capacitance change must be converted and simplified by a signal processing circuit, such as the commercially available one, which is thought to be difficult for capacitive transducers.^[91] Furthermore, hysteresis and cross-talk have reduced the repeatability of capacitive sensors, limiting their use in very high-precision applications. Also, electromagnetic interference with neural or cardiac activity has restricted their use in heart and brain surgery.^[92] So far, the existing literature's stabilizability and biocompatibility have not been evaluated.^[87]

The last type of sensors in this category is piezoelectric sensors, which rely on the piezoelectric effect, wherein imposed mechanical forces onto a piezoelectric element (normally made of polyvinylidene fluoride—PVDF) led to measurable generated charges that can be harvested as the output voltage (Figure 5d). The relationships between the electromechanical effects used in the design of piezoelectric sensors can be obtained as:^[84]

$$V = f\sigma \quad (4)$$

where V is the generated voltage; σ presents the induced stress by physical loading; and f denotes a constant coefficient. Finally, the produced mechanical strain can be defined as:^[84]

$$\epsilon = Vd \quad (5)$$

where $d = \frac{1}{fE}$ is the piezoelectric coefficient with Young's modulus E of the piezoelectric material. Piezoelectric sensors are suit-

able for a variety of force-sensing operations due to their stability, repeatability, and linearity, among other significant features.^[93] As the result, piezoelectric sensors have been used in many studies for surgical instruments such as MIS graspers,^[94] biopsy needles,^[95] and the surgical catheter.^[96] This kind of sensor, however, is prone to charge leakage and is unsuitable for low-frequency applications. Additionally, it is sensitive to temperature fluctuations from the environment and is unable to detect static loads for extended periods of time.^[1,87,97]

3.1.2. Optical-Based Sensing

One of the well-known sensing methods that have been developed and employed in numerous cutting-edge surgical instruments of TSRSs is optical sensing. This sensory genre can modify the characteristics of the light, such as intensity, wavelength, amplitude, and phase as the results of external changes (e.g., pressure, strain, acceleration, temperature, electromagnetic fields, or even chemical compositions) in a specific manner. The optical signal can either be sent via fibers for distal processing or locally turned into electric signals.^[98] To date, there are three generations of optical sensors including light intensity modulation (LIM), wavelength modulation or Fiber Bragg Grating (FBG), and phase modulation or Fabry-Perot interferometry (FPI) based optical sensors. Even though FBG sensors can obtain higher resolution measurements than LIM sensors, the signal processing of FPI sensors is simpler and does not necessitate complex signal processing algorithms. The detail comparisons between three optical sensor generations were presented by Bandari et al. in their study.^[84] Figure 5e shows an example of three optical force sensors used for a radiofrequency ablation catheter.^[99] The most significant advances in optical sensors are biocompatibility and magnetic resonance imaging (MRI) compatibility, therefore the optical-based sensors have been the only MRI and electrically passive sensing modalities in MRI-guided surgeries.^[100] In addition, this sensory type can be easily miniaturized, lightweight, and flexible in designs, while remaining high in sensitivity and large in bandwidth. Thus, they have been used widely for both force and tactile sensing in advanced surgical instruments.^[84,87] Nonetheless, fiber optic sensors have significant drawbacks that may be deal breakers for developing easily produced, low-cost sensors for TSRS surgical instruments. Therefore, fiber optic sensor systems are frequently more expensive than nonoptical alternatives.^[101] Additionally, due to the constraint of very large curvature radii, fiber sensing cannot handle the high bending strains of several surgical robotic equipment. For instance, FBG sensors cannot pass across the joints linking tool stem to tooltip such as for endowrists, or it is not feasible to directly connect them to the dexterous continuum manipulators.^[102]

3.1.3. Other Sensing Technologies

Here, we give a brief discussion of further new sensing technologies that could be applied to the sophisticated surgical tools in TSRSs. Shape memory alloys (SMAs), such as Nitinol, which are inexpensive, have a high gauge factor compared to typical metallic strain gauges, and provide a greater range due to their stretchability, are an alternate technique to develop sensors for surgical

tools (Figure 5g).^[104] However, in applications requiring dynamic loading, they are temperature-sensitive and incorrect.^[87] The technique of employing accelerometers to measure the vibration frequency and phase shifting to estimate force is another sensing approach. This method notwithstanding is slow since it takes a few vibration cycles to provide steady, dependable signals.^[105]

Recent advances in microfluidic-based soft sensors (Figure 5c), which are formed by injecting a small volume of the liquid medium into elastomeric microchannels, have the potential to increase the practicality and adaptability of force and tactile sensing.^[21] They can enhance the tissue grasping and manipulation tasks allowing stable grasps with fewer forces, and enabling palpation to detect the geometry, mechanical characterizations, and location of the tissue in contact with a surgical instrument.^[106] Nonetheless, leakage is the major problem of this approach, as a result, proper sealing of the working liquid is required for MIS applications while using this biocompatible elastomeric structure.^[21]

In attempts to increase tool dexterity and safe tool–tissue interactions during surgical operations, numerous research has used continuum robots and soft materials for the slave robots of TSRSs.^[107] However, because of the utilization of these technologies, direct force sensing implementation based on micromechatronic components or soft-stretchable materials may result in greater complexity.^[85,108] Fortunately, new approaches have recently been developed, which leverage endoscopic vision with the usage of responsive materials, to induce force sensing through vision. Vision-based assessment of the applied force on tissue is accomplished mostly by analyzing collected pictures with a camera and integrating the obtained data with a mathematical model of the organs.^[20] For example, Giordano et al. introduced a direct force sensing strategy based on visual feedback for a soft grasper with force cues based on mechanochromic-driven color changes close to the end effector (Figure 5f).^[85] Despite advances, further improvements are required to make this method suitable in real-life for any type of surgery, endoscopic camera, and imaging capabilities, with no prior customized model of the abdominal organs in real time.^[20]

Recently, hybrid setups combining two or more sensing approaches have become available.^[109] For example, a hybrid piezoresistive-optical-fiber sensor used for surgical tools in MIS was proposed by Bandari et al. in a study.^[109] However, multi-sensor crosstalk, noise amplification, varied refresh rate, sensor asynchrony, and rising system complexity remain technological and methodological challenges.^[84] Magnetic sensors and related composites are also other types of soft sensing technologies for surgical systems.^[110]

3.2. Actuation Technologies and Typical Haptic Devices

In haptic interfaces, the actuators are used to render/ produce force or tactile sensations to the surgeons. To be efficient and transparent, these actuators need an efficient control law for reducing friction, nonlinear hysteresis, and inertia. Furthermore, the actuators should be designed to avoid high-voltage, high-current, high-pressure, and excessive noise, to ensure patient and surgeon safety and comfort.^[85,111] This section will look at con-

ventional actuators found in existing haptic interfaces, as well as new actuators with tremendous potential.

3.2.1. Conventional Actuators

Standard actuators used in most commercial haptic devices include electrical actuators, pneumatic actuators, and hydraulic actuators. Electric DC motors and electromagnetic or vibration actuators are one of the traditional forms of electrical actuators (Figure 6a).^[11,20,85,111,112] They have been the main power source in many haptic interfaces because they offer fast responses, precise position and force control as well as non-disturbance with a low noise level.^[111,113] Therefore, they have been widely implemented in commercial haptic interfaces such as Geomagic Touch from 3D systems, Omega.3 from Force Dimension, or other developing haptic devices.^[114] Pneumatic actuators are another alternative option for electric motors as they offer a low mass and employ compressed gasses to generate a mechanical motion with a wide range of motion.^[115] These features allow for the realization of sophisticated, multi-DOF kinematic structures in a compact package, making them highly suited for haptic interfaces at the master console.^[116] Pneumatic artificial muscles (PAM) are one of the typical types of pneumatic actuators. It is worth noting that the use of pneumatic actuators requires a compressed air source which enables the simultaneous control of multiple PAMs within haptic interfaces with higher DOFs.^[117] Although PAMs have been widely used, non-negligible hysteresis, restricted displacement (elongation), and limited lifespan remain their disadvantages.^[118] An example of the use of PAMs in haptic devices can be found in the work developed by Lee et al. (Figure 6b).^[119]

In contrast to the pneumatic actuator, hydraulic actuators employ liquid (water, oil, and other liquid forms) as stimulants to provide a high power-to-weight ratio, allowing them to exert enormous force.^[120] However, hydraulic actuators are generally costly, requiring a complicated and constrained mobility system to supply high pressures.^[121] The recent use of hydraulic actuators for haptic devices has attracted attention. For example, Thai et al. used hydraulic actuators for a finger-worn skin stretch haptic interface with a tactor, which could induce 3-axis tangential forces to the skin (Figure 6c).^[122]

3.2.2. Emerging Actuators

Compared to conventional actuators, new haptic actuators have been created to provide better flexibility. They typically include piezoelectric actuators, shape memory alloys (SMA), electroactive polymers, soft magnetic materials, series electric actuators, and hybrid actuators. They are made of smart materials that can vary considerably in response to external stimuli including stress, strain, temperature, moisture, pH, and electric or magnetic fields.^[128] Haptic interfaces based on these new actuators are currently only accessible in laboratories and are not yet commercially available. Piezoelectric actuators employ ceramic crystals to alter their form and create force when a high voltage is applied. They are well known for providing tactile feedback information. An example is the Exeter interface which was developed

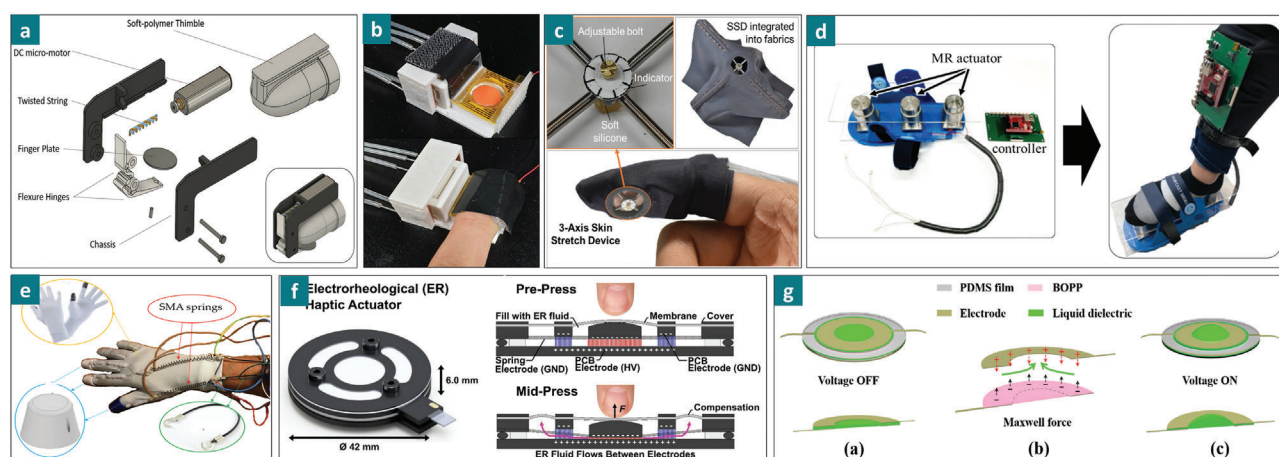


Figure 6. Examples of conventional haptic actuators: a) Electrical actuator (DC micro-motor) in the haptic Thimble. Reproduced with permission.^[123] Copyright 2021, MDPI; b) Pneumatic actuator in a finger pad display. Reproduced with permission.^[119] Copyright 2021, MDPI; c) Hydraulic actuator in a finger-worn soft skin stretch device. Reproduced with permission.^[122] Copyright 2020, IEEE; Examples of new haptic actuators: d) The use of three magnetorheological (MR) haptic actuators in a shoe. Reproduced with permission.^[124] Copyright 2021, MDPI; e) A haptic glove with SMA actuators. Reproduced with permission.^[125] Copyright 2021, MDPI; f) Structure and working principle of electrorheological (ER) haptic actuator. Reproduced with permission.^[126] Copyright 2021, MDPI; g) Main components and working principle of a hybrid (electro-hydraulic) actuator for the soft wearable device. Reproduced with permission.^[127] Copyright 2020, MDPI.

to stimulate tactile sensations on the fingertip.^[129] Additionally, piezoelectric actuators have several other advantages such as high resonance frequency (about 100 Hz), high stiffness (0.3 to $2.3 \text{ N } \mu\text{m}^{-1}$), and capacity to generate a large force despite a small amplitude and size.^[130] However, due to their characteristics, the displacement is extremely small, approximately a few μm . SMA actuators are another technology used in the haptic interface of the master console. The SMA has a particular property of returning to its former shape when the appropriate thermal heating is applied. During this transition, the SMA produces a force that could be utilized to reproduce force feedback in the haptic system. It is worth noting that SMA actuators can produce more useful work per unit volume than most actuating mechanisms. Chernyshov et al. proposed a novel wearable haptic device using SMA wires for providing pressure-based haptic feedback.^[131] Terrile et al. developed a soft haptic glove for kinesthetic perception actuating two fingers with two SMA springs (Figure 6e).^[125] More recently, Muthukumarana et al. presented a wearable forearm augmentation using an SMA actuator, that can create shear forces onto the skin enabling the recreation of natural touch sensation.^[132] However, the major disadvantage of these haptic actuators is their response, which may be slow for haptic applications.^[111]

Passive actuators such as brakes and dampers are other alternative approaches for standard electric motors, that could produce force feedback by dissipating kinetic energy and are thus intrinsically stable.^[133] The most common types of these passive actuators are electrorheological (ER) and magnetorheological (MR) brakes that both use a liquid substance to change its apparent viscosity under the influence of a magnetic or an electric field. They can create a wide range of impedance that is higher than that of electric motors at the cost of a longer response time.^[134] For example, Mazursky et al. presented the design and experimental evaluation of an ER haptic actuator in realistic applications (Figure 6f).^[126] Heo et al., on the other hand, proposed the use of an MR haptic actuator for a shoe (Figure 6d).^[124] However, both

MR and ER brakes have a higher torque-to-mass ratio compared to conventional DC motors, resulting in excellent haptic transparency. An electrostatic (ES) brake is another form of passive actuator that can be used to create substantial force. For example, Hinchet et al. designed a wearable device using an ES brake to produce arresting forces of 20 N for kinesthetic feedback.^[135] Unfortunately, passive actuators can only generate forces in the opposite direction of the input velocity, making controlling the direction of the output force in multi-DOF devices difficult.^[114]

Electroactive polymers (EAP) are a promising technology that can result in a change in shape or size with electrical stimulation. Their advanced features include great power efficiency, high flexibility, high dynamics, resilience to damage, and being light in weight, making them highly suited for wearable devices where compliance and adaptability to complex surfaces are desired.^[136] For example, Mun et al. presented a soft tactile interface using multi-layered and thin EAP films that could be embedded into the fingertip of a wearable haptic glove.^[137] Although this device could produce a haptic sensation to the wearer, its inherent drawbacks include high applied voltages and a complicated fabrication process, making commercialization difficult.^[111] Series electric actuators (SEA) are another innovative technique where an elastic element is inserted between the mechanical drive and the end effector. This architecture allows a great response of stiffness structures to applied input forces. Because the elastic element is used to provide a direct force estimate, the SEA is topologically more conducive to accurate force control than other conventional actuators.^[138] Although it is counterintuitive for a haptic device to be added an elastic element, there are numerous benefits over rigidly coupled actuation such as improvements in shock tolerances, force control, stability, and efficiency. Additionally, they also allow for decoupled actuator inertia and decreased frictional effects, making them a good base for force feedback devices.^[139] Alternatively, they can achieve good force bandwidth with a low output impedance when being under closed-loop force control.

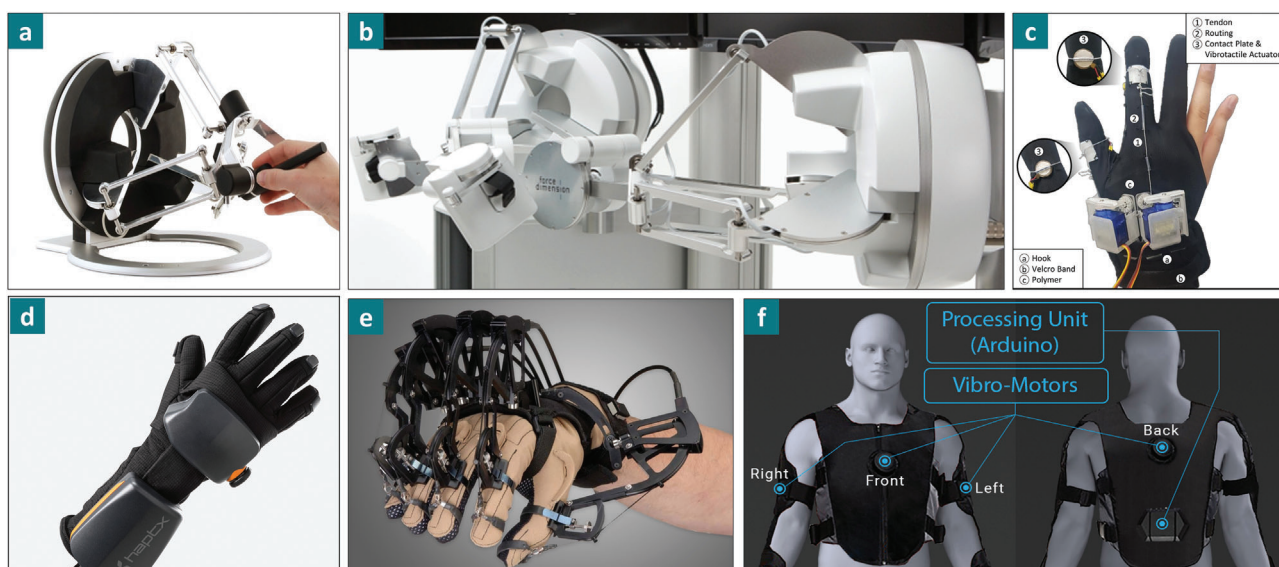


Figure 7. Examples of typical haptic devices in the market and literature: a,b) Omega.6 and Sigma.7. Courtesy of Force Dimension, Switzerland.^[141] Copyright 2022, Force Dimension; c) Stiffness rendering wearable haptic glove. Reproduced with permission.^[144] d) HaptX Glove G1 system photo provided courtesy of HaptX, Inc.^[151] Copyright 2022, HaptX, Inc.; e) CyberGrasp (CyberGlove Systems Inc., California, USA). Reproduced with permission.^[152] Copyright 2017, CyberGlove Systems Inc.; f) Vibrotactile feedback VR suit. Reproduced with permission.^[153] Copyright 2021, MDPI.

However, the primary drawback of SEAs for haptic rendering is a limitation of the elastic element to reach maximum stiffness.^[113]

The last category of haptic actuators is hybrid approaches where actuators are a combination of two or more distinct actuation techniques (Figure 6g) to overcome their constraints. Typically, a hybrid actuator is made of an active element for energy restitution and a passive actuator to enhance torque capabilities and dissipate energy as required. With all possible developments, this method might eventually lead to the construction of transparent haptic interfaces for surgical master consoles.

3.3. Typical Haptic Devices

Recently, it has become more and more common to employ a commercial haptic device in TSRSs for MIS procedures. Here, we discuss the available haptic devices, their prospective applications, and the status of haptic display utilization in TSRSs. Typically, the existing haptic interfaces can be divided into three main categories: graspable, wearable, and touchable devices.^[140] Graspable devices are archetypically kinesthetic or force-feedback systems that are anchored, for example on the desktop, and provide the user the ability to manipulate objects by pushing and pulling movements using a graspable tool. Haptic devices such as the Omega series (Figure 7a), and Delta.3, Sigma.7 (Figure 7b), and Lambda.7; from Force Dimension (S.A., Nyon, Switzerland) are the most commercially available graspable haptic interfaces systems, which are widely used in many TSRSs. Other notable devices within this category are the Phantom desktop^[141] or TouchX and Geomagic Touch from 3D SYSTEMS (Rock Hill, South California, USA)^[142] or the Novint Falcon from Novint Technologies (Albuquerque, New Mexico, USA).^[143] These graspable haptic devices are usually actuated by electric DC motors which can provide 3D active force feedback information to users with multiple

DOFs. These systems can be also employed in a wide range of applications including medical robotics, teleoperation consoles, virtual simulations, and training systems. However, as was already said, using desktop devices with hard components might make surgeons uncomfortable and exhausted.

The second category is wearable devices which are typically cutaneous or tactile systems that are worn on the fingers, hands, or other body parts of humans, directly transferring sensations to the skin. For the wearer, this type of haptic device can relay other haptic information including vibration, lateral skin stretches, and normal skin deformation. For example, Lee et al. suggested using a wearable haptic glove with a tendon-based transmission mechanism, which can produce kinesthetic feedback powerful enough for immersive manipulation and interpenetration prevention in a small-form-factor, while maximizing wearability and minimizing occlusion in AR use (Figure 7c).^[144] The level of wearability of haptic interfaces can be identified by their form factor, weight, shape, area of interest, and ergonomics, according to works reported by Pacchierotti et al.^[145] The devices' wearability level is determined solely by their design characteristics. For example, the fingertip haptic device can be regarded as more wearable than a hand exoskeleton, which can be considered more wearable than a full-body exoskeleton such as the Raytheon Sarcos' XOS 2 robotic suit. Figure 7d,e present two examples of haptic gloves including HaptX glove G1 (HaptX Inc., Washington, USA) and CyberGrasp (CyberGlove Systems Inc., California, USA), which are commercially available. Figure 7f depicts another haptic suit developed by Mirzaei et al., which can provide vibrotactile feedback used in the virtual environment.^[153] Wearable devices differ from desktop haptic devices in several ways, including their ability to support large-scale body motions and their ease of donning and taking off.^[146] The third category is touchable haptic systems that are encountered type displays. These devices enable the user to probe the entire surface actively. They can be simply cutaneous

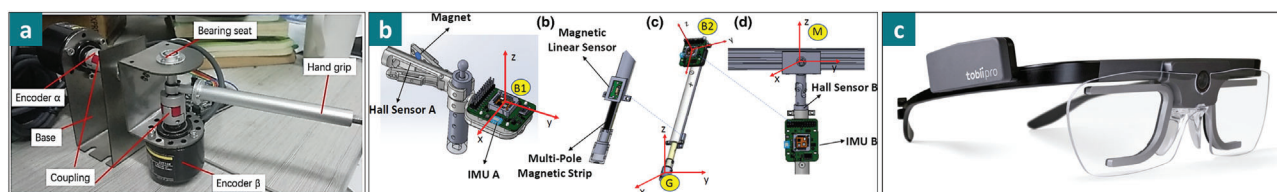


Figure 8. Examples of sensing technologies for the master consoles: a) Encoders used for the master surgical manipulator. Reproduced with permission.^[155] Copyright 2021, MDPI; b) Magnetic linear sensors and IMU sensors used in a master console of the Hamlyn CRM. Reproduced with permission.^[17] Copyright 2020, Springer Nature; c) Tobii Pro Glasses 2 eye-tracker (Tobii Inc., Danderyd Municipality, Sweden). Reproduced with permission.^[163] Copyright 2020, MDPI.

devices that alter their tactile characteristics by location such as a surface with variable friction. The touchable devices can also be hybrid cutaneous and kinesthetic devices that change their shape, mechanical properties, and surface properties.^[140,146] This type of haptic device might be useful for the control panel of the master console, however, it requires constant contact.

Currently, haptic technologies are being employed in a growing number of commercially accessible surgical robotic systems, proving their capabilities and importance. The Senhance surgical robotic system, as described in Section 2.1, has demonstrated an enhancement in MIS procedure, compared to the da Vinci system, by coupling haptic feedback via two force feedback manipulators. These manipulators transmit gripping force to the surgeon at the master console, allowing tissue gripping consistency or precise object manipulation.^[147] Bozzini et al. demonstrated that the instructive capabilities were achieved during thread and needle manipulation while suturing with haptic feedback.^[148] Spinelli et al. revealed the possibility of transmitting tissue resistance to the surgeon's cockpit and confirmed that applied grasping tension on tissue in colorectal surgery could be optimized if haptic feedback was integrated. This characteristic can be beneficial in minimizing the risk of damage to organs and delicate structures, especially if the instruments are accidentally moved outside of the optical viewing zone.^[149] The integration of haptic functionality into the REVO-I system has been recognized as a major technological element that distinguishes it from the famous da Vinci surgical system. Despite limited technical specifics on its use and implementation, the REVO-I system provides the surgeon with force feedback from surgical graspers and actively adjusts instrument speed and force within set "safe" limits.^[35,150]

4. Sensing Technologies for Advanced Master Consoles

It is critical to provide precise motion tracking for the master consoles to ensure the safety and precision of the remote control of the slave manipulator within the human body. The use of sensors enables the slave manipulator to respond precisely to the operator's orders via the master console to execute surgical operations with high efficiency, which is regarded as a critical component of a teleoperation system.^[17] This section will introduce current sensing technologies used for the master console and their potential for future teleoperated surgical systems.

Position sensors are one of the most prominently used sensing technologies that can detect the motion of an object or define its relative position from a given reference point. They can

also be used to detect the presence or absence of an object.^[154] These sensing technologies are used in the master console of surgical robotic systems to track and detect the surgeon's movements while doing procedures, and then translate the data to operate the slave instruments. The most common position sensors are analog potentiometers and digital encoders. They are electromechanical sensing devices where motion inputs are converted to electrically readable signals. Many user interfaces for surgical systems have used position sensors as the main components to record user inputs. For example, Shi et al. employed two encoders to detect the rotation angle of a master surgical robotic manipulator (Figure 8a). The encoder signals are sent to the microprocessor, which is then used for the posture control of the end effector connected to the surgical slave manipulator.^[155] In the context of NOTES, Phee et al. presented the design of a master and slave transluminal endoscopic robot that used a set of encoders to capture the surgeon's movement and deliver data to the computer console. The encoder signals were interpreted by the computer's CPU and motion controller, which drove DC motors to remotely actuate the slave manipulators via tendon sheath mechanisms.^[156] Similarly, Do et al. integrated several encoders into the master console which was then used to manipulate a flexible surgical robotic arm using a nonlinear adaptive control algorithm. The encoders were mounted on the master-grripper to provide the necessary position-reference trajectory to output pulleys located at the motor housing side. The signals were then processed by a controller for manipulating a surgical gripper integrated into a conventional endoscope.^[157] Although it is stable and reliable, the employment of an encoder is inappropriate for compact-designed master consoles.^[17,158]

Another form of position-sensing technology is the Hall effect-based magnetic position sensors, which employ the Hall effect to measure the position of an object by attaching it to a magnet contained in the sensor shaft. The relative position of the magnet and the Hall element in the sensor, as well as the magnetic field intensity, vary when the object moves. This is applied to the Hall element, resulting in a change in the measured Hall voltage representative of the object's position.^[154] For example, Zhang et al. proposed a Hall effect-based magnetic position sensing system comprising multiple sensors for motion tracking of the Hamlyn Compact Robotic Master (CRM). The system used two Hall sensors and one magnetic linear sensor for each master manipulator (Figure 8b). The magnetic linear sensor was an incremental position sensor with on-chip encoding for direct digital output, wherein the incremental position of an external strip was determined by a Hall element array on the device. The magnetic linear sensor is a reliable and cost-effective sensor

for linear position detection because of its greater resolution of around $0.5\ \mu\text{m}$.^[17]

Besides position sensing, data of the body's specific force, angular rate, and direction can also be detected and transmitted by the inertial measurement unit (IMU) sensors for the master consoles of TSRSs. This type of sensor comprises accelerometers, gyroscopes, and magnetometers that navigate independently the positions of an object to which it is attached.^[159] In 2016, Yu et al. presented the use of IMU sensors to track the mobility of both assisting and console surgeons during robotic prostatectomy procedures (Figure 8b). The IMU devices were worn by the surgeons to track their continuous neck, shoulder, and torso motion without interfering with a sterile environment. Sensing data were collected during the procedure and then analyzed to report postural angles using MATLAB programs (R2015b, MathWorks Inc., Natick, MA, USA). The IMU sensors were successfully implemented to assess the ergonomics of robotic prostatectomy cases.^[160] Similarly, Sani et al. developed a custom finger tracking system using IMU sensors to analyze the finger motion during cardiac surgery tasks on an ex vivo animal model, aiming to design a more intuitive master console. Finger joint angles and fingertip position of the thumb, index, and middle fingers were tracked by the sensing system.^[161] Unlike wearable IMU sensors, the Hamlyn CRM sensing system, mentioned above, also contained two 9-axis IMU sensors (Mti-3, Xsens): one installed on the handheld end-effector controller to detect its orientation, while the other one was placed on the linear linkage to monitor its orientation. Their data were collected by controlling the end-effector to perform repeated translational motions. Furthermore, Zhang et al. concluded that the use of sensor fusion with multiple sensors (IMU, Hall, and magnetic linear sensors) for the Hamlyn CRM sensing system successfully enhanced tracking motion accuracy.^[17] Despite a sophisticated setup, the IMU data can be incomplete, inaccurate, or error prone. The key variables are a gravity force encountered by the IMU device, which might taint accelerometer data; nearby magnetic disturbances can have impacts on magnetometer measurements and unbounded time-varying matters may cause gyroscope data to wander.^[162]

Eye-tracking sensors are another important sensing technology for the master console in teleoperated surgical systems. This type of technology is often composed of cameras, projectors, and algorithms. The projectors cast a pattern of near-infrared light on the eyes, wherein the cameras capture high-resolution images of the pattern in the user's eyes. The eyes' location and gaze point are determined using machine learning, image processing, and mathematical techniques.^[164] The Tobii eye-tracking sensor is one of the most common-used sensors which has been employed in a variety of devices such as in a lightweight pair of glasses named Tobii Pro Glasses 2 (Figure 8c). In surgical robots, eye-tracking systems have been widely employed, particularly in tracking the surgeon's gaze at the master console while executing procedures. For instance, Wang et al. proposed a method of Master-slave motion alignment for an open surgical console.^[19] Similar to Tobii Pro Glasses 2, Microsoft HoloLens 2, a potential alternative to conventional monitors in endoscopic surgery,^[165] also offers an eye-tracking sensor to make interactions feel more natural.^[166]

Recently, sensors have been widely used to monitor human activity for a variety of applications such as medical rehabilita-

tion, healthcare monitoring, and fitness or sports tracking. These sensing architectures might be useful for the future of TSRSs' advanced master consoles. For example, Huang et al. used a sensor fusion method including force sensors and electromyogram (EMG) sensors to capture the motions of lower limb handicapped patients when interacting with leg robotic exoskeletons. While the desired motion of a patient was detected by pedal-based force sensors, the EMG sensors were positioned at the left and right gluteus Medius muscles to evaluate the useful assistance of the exoskeletons.^[167] In another approach, Bravi et al. used two IMU sensors employed on the wrist and upper arm for detecting shoulder range of motion in cervical spinal cord injury patients^[168] while Regterschot et al. assessed arm use in stroke patients impacted by whole-body motions using wrist-worn accelerometers.^[169] Wilmes et al. introduced an easy-to-use motion analysis system with inertial sensors in football practice to enhance the physical load estimates of the players by acquiring lower body kinematics and quantifying movement intensity.^[170] Lin et al. employed sensing fusion of inertial sensors and magnetometers in a head-mounted system in the form of a pair of glasses to detect falling movements in daily life.^[171] With its various application capabilities, advancement, and compact size, the IMU sensor holds a lot of potential to be employed in the master console of TSRS the surgeon motion tracking.

In attempts to enhance the master console ergonomics, the technology of incorporating a variety of sensors into smart gloves for motion tracking has been developed. For example, Manus Prime II Xsens (MANUS, Geldrop, Netherlands), a commercialized glove has been developed by combining flex sensors with IMU sensors. This smart glove offers finger tracking with 11-DOFs for the full finger ensuring the finest motor movements.^[172] Another commercialized smart glove named MoCap Pro glove by StretchSense offers a solution for film and gaming animation. It has a three-sensing area (variable capacitance) splay sensor that can detect the motion of each proximal interphalangeal (PIP) and metacarpophalangeal (MCP) joint and the sideways splay or finger spread of each digit.^[173] Unlike the MoCap Pro glove, the 5DT data glove was built by Fifth Dimension Technologies to satisfy the high standards of modern motion capture and animation professionals. This smart device uses 11 patented optical-fiber flex sensors mounted in a textile substrate crossing the MCP and PIP joints of the fingers and the interphalangeal (IP) and MCP joints of the thumb in small fabric pockets.^[174] The trend of incorporating sensors into textile gloves for a variety of applications has grown in recent years. In 2020, Hughes et al. integrated hybrid resistive-pressure sensors into a simple, low-cost, wearable glove, which was able to reconstruct real-time hand pose, sense the environment, and classify tasks.^[175] In 2021, Guo et al. explored the transplantation of a flexible sensor to a data glove to track the bending changes of the knuckles for simple gesture recognition and rehabilitation training.^[176] Similarly, Yang et al. employed a flex sensor in a hand-sensing glove to measure the hand motions, which was designed to be attached to a compact and portable hand exoskeleton for bilateral hand training and home-based rehabilitation.^[177] Although these sensing technologies are not directly used in teleoperated surgical systems, their ability to capture the motion of human limbs is high, and therefore they can be used in the future development of advanced TSRS user interfaces.

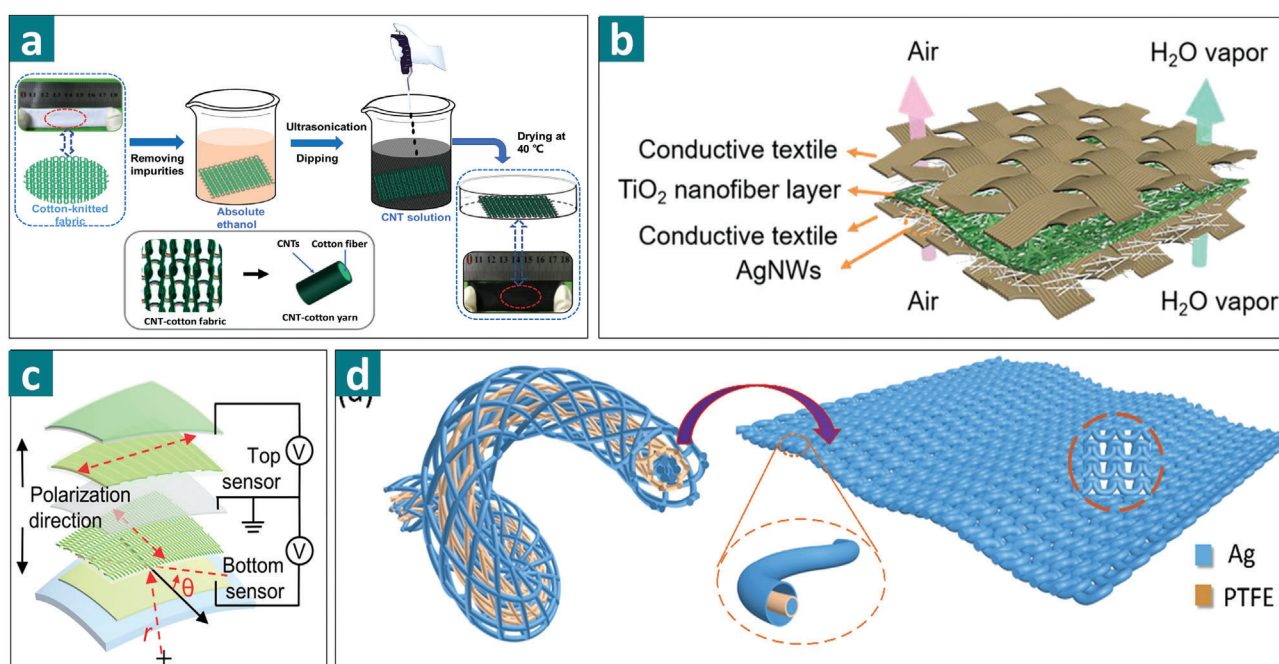


Figure 9. Examples of textile-based sensors: a) Preparation process of carbon nanotubes (CNTs) cotton fabrics (CCF) for CCF-based strain resistive sensors. Reproduced with permission.^[181] Copyright 2018, MDPI; b) Schematic of a capacitive pressure sensor based on flexible ceramic nanofibrous networks. Reproduced with permission.^[184] Copyright 2020, Wiley Online Library; c) The bending angle and bending radius of the double-layer kirigami structures highly anisotropic piezoelectric network composite (HAPNC) sensor with the top and bottom sensors. Reproduced with permission.^[186] Copyright 2021, AAAS; d) Shape-adaptive electronic textiles (SET) structure of coaxial fiber triboelectric sensors. Reproduced with permission.^[187] Copyright 2019, Wiley Online Library.

5. Smart Garments for Wearable Master Consoles

Over the last decade, the robotic fields have begun to adopt textiles to construct wearable robots and devices. This paradigm shift has happened because smart garments or e-textile-based interfaces can provide the necessary stimuli and produce a sense of user-device interaction. The level of intelligence of smart textile systems can be categorized into passive and active ones.^[178] Advanced wearable master consoles using superior smart garments should typically include textile sensors and embedded wearable electronics systems that enable registration and transmission of physiological data and wireless communication between surgeons and surgical systems.

5.1. Textile-Based Sensors

Passive smart garments or textile-based sensors can only sense the environment and users. There are a variety of textile-based sensors being applied in medical applications such as textile-based chemical sensors for human biomolecule analysis, humidity, and sweat detection, or textile-based physical sensors for sensing temperature, pressure, and obstacle of human-environment interaction.^[179] These textile-based sensors can be classified by their structures such as fiber- and yarn-based sensors, textile-structure-based sensors, and textile composite sensors.^[125] Passive smart garments incorporated into wearable devices for master consoles can be used to capture the surgeon's motions which subsequently control the slave manipulator. In this case, it will convert mechanical stimulus information created by the sur-

geon into electrical signals. According to the sensing mechanism, there are four main textile-based mechanical sensors namely resistive, capacitive, piezoelectric, and triboelectric sensors.^[180]

Textile-based resistive sensors use piezoresistive materials to transform mechanical stimuli such as displacement or force into a resistance change. Because the resistance of conductive material is defined as $R = \rho L/S$, a mechanical stimulus that produces changes in resistivity (ρ), length (L), and/or cross-sectional area (S) in piezoresistive materials will result in a resistance change. The variations in the resistance of sensing elements, devices' geometry, and base materials determine the resistive sensor's response. Textile-based resistive sensors are typically made up of a soft substrate (silk, cotton, polydimethylsiloxane (PDMS), polyurethane (PU)) and a sensing material (carbon materials, metal materials, conductive polymers). They can be fabricated in a variety of ways including coating, depositing, winding, or electroplating a functional conductive layer on fibers, yarns, or fabrics, as well as wet spinning or 3D printing processes.^[180] Two examples of textile-based resistive sensors include conductive cotton fabric resistive sensors^[181] (Figure 9a) and polymer-enhanced highly stretchable conductive fiber resistive sensors.^[182] Although textile-based resistive sensors have substantial benefits of high sensitivity, broad detection range, high accuracy, and simple measurement circuits, their main limitations include large-signal drift, poor durability, and evident hysteresis that limit their use in practice.^[183] Textile-based capacitive sensors, on the other hand, respond to the capacitance of sensing devices produced by external mechanical stimuli with fabrication methods for capacitive sensors similar to

resistive sensors. However, they require two electrode layers made from electrical conductivity materials (conductive fabrics, metal wires, carbon materials) and a dielectric layer with a large electric constant to reduce leakage current (elastic polymers, fabric gaskets, ionic gels).^[180] Fu et al., for instance, suggested a capacitive pressure sensor based on flexible ceramic nanofibrous networks that have sensitivity ($\approx 4.4 \text{ kPa}^{-1}$), an extremely low limit of detection ($< 0.8 \text{ Pa}$), a quick reaction time ($< 16 \text{ ms}$), and minimal fatigue (Figure 9b).^[184] While capacitive sensors offer good response repeatability, minor signal drift, long-term cycle stability, and low energy consumption, they are vulnerable to external field interference and have poor sensitivity and a restricted detection range. Textile-based piezoelectric sensors can transform mechanical stimuli into voltage signals by employing piezoelectric effects from flexible materials with the piezoelectric constant dictating the sensors' effectiveness. Piezoelectric sensors can be self-powered while achieving pressure sensing with piezoelectric materials including composites, polymers, ceramics, and single crystals.^[180] Sandwich structure for the piezoelectric sensors^[185] (Figure 9c) and double-layer structure for piezoelectric sensors^[186] are prominent examples. Piezoelectric sensors frequently have rapid reaction times and high sensitivity, making them ideal for use in wearable devices.

Another type of passive smart garment is the textile-based triboelectric sensors, which are made by combining the electrification/triboelectric effect with electrostatic induction in a variety of materials, such as synthetic polymers and natural silk, wool, and cotton. This type of sensor, like piezoelectric sensors, can translate mechanical motion into electrical impulses. Triboelectric sensors are made up of two electrodes with opposing tribopolarities. It is worth noting that the higher the tribopolarity difference between the two electrode materials, the better the sensors' electrical performance. Nylon, cotton, silver, and copper offer positively charged materials while PDMS, PVDF, and polytetrafluoroethylene (PTFE) provide negatively charged materials. Triboelectric sensors can be fabricated by weaving two frictional electrical sequences into fabrics or textiles to achieve a single yarn device, for example, coaxial fiber triboelectric sensors^[187] (Figure 9d); or by directly weaving two types of yarns or fibers with inherently different tribopolarities, for instance, double-layer triboelectric sensors.^[188]

5.2. Active Smart Garments

Active smart garments can sense the interaction with the surrounding environment and provide active motion or deformation to control objects that they are communicating with. The active smart garments are typically made up by integrating both textile-based sensors and actuators into one structure. To implement the active smart garment into wearable devices of the TSRS master consoles, the actuators of active smart textiles need to provide stimuli to the users. Three primary textile-based actuator mechanisms can be used including cable-driven actuators, fluidic actuators, and shape-changing material textile actuators. Specifically, a cable-driven textile actuator comprises a passive, stiff cable that can generate a force on the textile by being pulled by an external mechanical actuation. These cables can be coiled around a mandrel or employed in a twisted string design, in which the cable's

twisting converts rotating motion into linear motion. Samper-Escudero et al., for instance, integrated a jacket with cable-driven actuation utilizing a variety of fabrics and deformable components to help with shoulder and elbow flexion (Figure 10a).^[189] Although this sort of actuator can rapidly generate enormous amounts of force, it is bulky and requires external actuation to operate.^[25]

Textile-based fluidic actuators, on the other hand, change the shape of textiles under an applied external liquid or air source which inflates a textile-based pouch or in-unison pouches. Elastic fluidic actuators, piston-cylinder fluidic actuators, and drag-based fluidic actuators are the three primary categories. Elastic fluidic actuators like McKibben actuators are best suited for usage as haptic actuators in wearable devices. These actuators have a fluidic pressurized expandable chamber that converts the expansion to a contraction force. Their internal structures, which are typically inspired by bioarchitectures, can be controlled to provide linear, torsional, and bending actuation.^[193] For example, Zhu et al. proposed a haptic sleeve, also called PneuSleeve (Figure 10b), which can render a wide range of haptic stimuli consisting of compression, skin stretch, and vibration. They are generated by controlling pneumatic pressure inside embroidered stretchable tubes. The actuation configuration includes two compression actuators on the proximal and distal forearm, and four uniformly distributed linear actuators around and tangent to the forearm.^[190] A novel class of programmable smart textiles was developed by Phan et al. using various techniques for knitting, weaving, and adhering fluid-driven artificial muscle fibers.^[191] The new smart textiles can perform multimodal movements and change shape to be used in a wider range of applications, such as compressing garments (Figure 10c), since they are very flexible, conformable, and mechanically programmable. Nonetheless, this type of actuator has poor portability due to requiring a large fluid tank and assorted control units.^[194] Fluidic actuators are also constructed of soft materials with hard elements, with difficulties in sealing. These actuators may perform extremely complicated movements, making them ideal for soft haptic exoskeletons. Shape-changing material actuators, by contrast, provide a diversified collection of material-based actuation mechanisms, allowing a wide range of stimuli to be used to actuate these systems, whether electronically or through environmental means. Many active yarn materials have been developed for application in wearable devices such as coiled polymer actuators and SMAs. For instance, Park et al. proposed a new type of soft wearable robot using an SMA-based fabric muscle as the actuation method (Figure 10d). This design could overcome the limitations of conventional robots in terms of weight and inconvenience, thereby demonstrating the application potential of the wearable device using textile-based shape-changing actuation.^[192] Although the textile itself is an active actuation component when shape-changing materials are built into textile designs, the device may still require other power components such as heavy batteries.^[25]

6. Vision Sensing and AI Assistance Technologies

In most circumstances, teleoperated surgical robots isolate the surgeon from the patient, resulting in sensory deprivation. Although attempts have been conducted to incorporate force

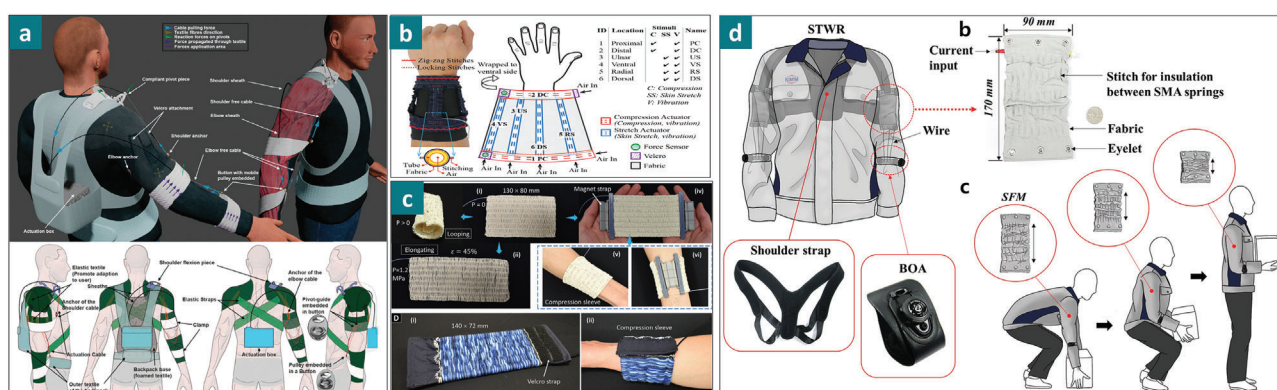


Figure 10. Examples of wearable devices using textile-based actuators: a) Portable cable-driven textile-based exo suit. Reproduced with permission.^[189] Copyright 2020, IEEE; b) PneuSleeve prototype, design, and actuation renderability. Reproduced with permission.^[190] Copyright 2020, ACM. c) Hydraulic compression garments using programmable smart textiles. Reproduced with permission.^[191] Copyright 2022, Springer Nature. d) Wearable suit using SMA-based fabric muscle. Reproduced with permission.^[192] Copyright 2019, Springer Nature.

sensors into the instrument to provide information to drive haptic devices, the use of onboard sensors is highly restricted by the tool size, biocompatibility, and sterilization requirements. In addition, the sensory instrumentation has also exacerbated safety concerns and thus poses a drive for more effective use of visual streaming data to give “information assistance”. Several vision approaches such as enhanced video displays have been used to give in vivo surgical guidance information and semantic feedback to surgeons, possibly boosting their awareness and target reachability and therefore improving overall patient safety in robot operations. These vision-sensing techniques can be classified as anatomical- or functional-sensing modalities.^[195]

Ultrasound, CT, MRI, and video capture via integrated on-board camera at the surgical site are examples of commonly utilized anatomical-sensing modalities that focus on collecting macromorphological or micromorphological features of the human body. Medical ultrasonography is often used to rebuild 2D pictures of human tissues based on the amplitude and elapsed time of reflected sound waves, and then give visual information to assist surgeons in planning and making decisions during MIS operations.^[196] Medical ultrasound’s major benefits include safety, low cost, and mobility, which have led to its widespread use in a variety of surgical applications. It also includes real-time imaging beneath the skin’s surface, which is difficult to do with CT or MRI techniques.^[197] To expand the view angle with the minimization of hand tremors, a combination of endoscope and ultrasonography has been used.^[198] The Flex Focus 800 ultrasonography system (ForTec Medical Inc., Hudson, OH, USA) is an enhanced imaging system that offers precise real-time imaging on a high-resolution 19 in. monitor display for intraoperative laparoscopic surgery and neurosurgery. It should be noted that the surgeon may detect and decide on uncertain tumor targets with indistinct characteristics utilizing this system.^[199] The Siemens ACUSON X600 is another well-known ultrasound system that can offer great image quality and dependability in a variety of advanced surgical applications. It supports automated tissue grayscale adjustment and is equipped with wireless data transfer, allowing daily and shared-service imaging to run more smoothly.^[200] Besides, ultrasound modalities have been employed to leverage surgical operations. For example, Han et al.

introduced a surgical robot that can sweep the transrectal ultrasound transducer using a joystick to capture different layers of the prostate and surrounding tissues. This gives surgeons an extra degree of freedom to look for malignant tissues deep within the prostate.^[201] Ultrasonic medical imaging can be used alone or in combination with MR and CT images to support needle insertion treatments for malignant tumors.^[197,202] Gilling et al. employed ultrasound in conjunction with MRI to track da Vinci surgical tools and regulate the sweep angle in the surgeon’s console for a robotic system. Because MRI is a good candidate for detecting malignant tissues, and ultrasound is good for updating pictures in real-time, surgeons have more information to make decisions.^[203]

CT and MRI, on the other hand, have been utilized in diagnostic cross-sectional imaging because they have better picture resolution than ultrasound.^[204] While CT is good at imaging hard tissue like bone, MRI is better at soft tissue such as muscle and cartilage. The main drawback of the CT is high radiation exposure making it less suited for repetitive surgery, whereas the intraoperative MRI system is accepted as a safe approach for surgery.^[205] Sequential CT/MRI data fusion is possible and safe for use in MRI-based preplanning with a soft tissue registration error that is acceptable.^[206] For example, Aquilion Precision is the world’s first ultra high-resolution CT from Canon Medical Systems (USA). The technology can identify anatomy up to 150 μm in size and recreate CT pictures with increased high-contrast spatial resolution. It also has a deep learning system that classifies signals from noise and doubles the resolution of traditional CT.^[207] The Philips Ingenia Elition solution (Koninklijke Philips NV, Amsterdam, Netherlands) provides cutting-edge MR imaging techniques while also setting new benchmarks for clinical research in 3.0 T imaging using gradient-based and RF-based designs (Figure 11). This device can produce excellent picture quality and perform MRI tests up to 50% quicker. Improved patient handling setup time at the bore with touchless guided patient setup, along with accelerations in both 2D and 3D scanning, results in a faster overall exam time. The Ingenia Elition also provides an immersive audio-visual experience to help patients relax and navigate MR tests.^[208] In a pilot study of intraoperative image guiding in transoral robotic surgery, Ma et al. collected CT images

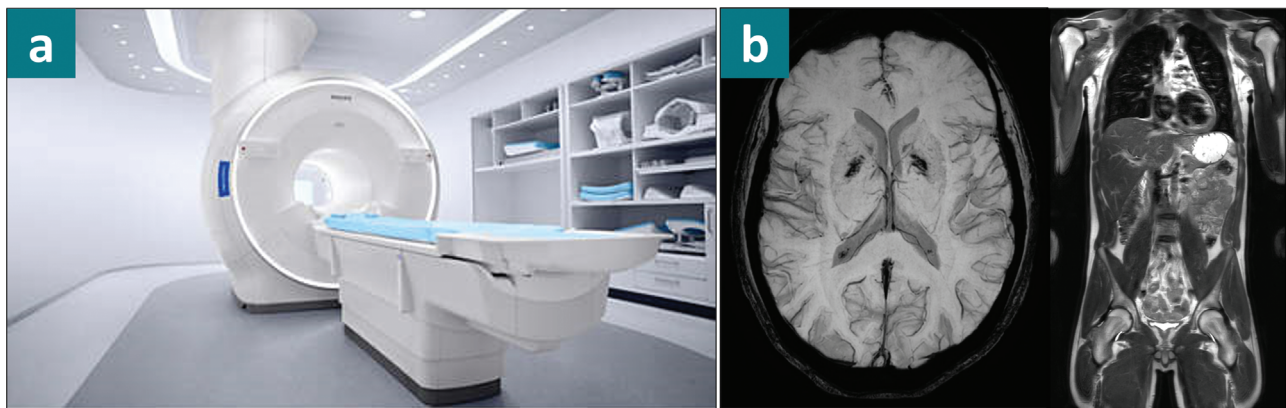


Figure 11. a) Philips Ingenia Elition 3.0T MRI solution system (Koninklijke Philips N.V., Amsterdam, Netherlands) and b) Examples of the clinical images produced by MRI systems. Reproduced with permission.^[214] Copyright 2022, Koninklijke Philips N.V.

in both the preoperative and intraoperative positions. The precision of registration was established in this work utilizing intraoperative cone-beam CT imaging.^[209] Real-time ultrasound data of the patient's head is gathered with the use of fiducial markers while the intervention is being carried out, and the plan is modified accordingly.^[210]

In neurosurgery, functional modalities such as (resting-state [Rs]) functional MRI (fMRI), diffusion tensor imaging (DTI), and functional ultrasound (fUS) have been increasingly used.^[211] Recent findings revealed that task-based fMRI and DTI tractography are reliable and sensitive techniques for locating the different eloquent cortical and subcortical regions in glioma patients before surgery. Compared to intraoperative stimulation mapping data, these technologies offer higher accuracy. The Rs-fMRI functional connectivity approach is redefining the role of fMRI in glioma surgery, with implications for individualized treatment methods.^[211] Meanwhile, the use of fUS in neurosurgery allows for real-time cortical functional mapping during tumor excision, allowing for more detailed delineation of cognitive regions while avoiding the loss of functionally important structures.^[212]

A real-time feed of the modular/stereo camera gives the surgeon a visual perspective on teleoperated equipment during the intraoperative stage. The major difficulties at this point are the limited field of view, the loss of depth perception associated with monocular cameras, and the absence of force feedback. Thus, the use of computer vision is necessary at this phase as it takes real-time visual feed and provides informative feedback through means of AR, tool tracking and posture estimation, simultaneous localization, and area mapping (SLAM) with higher-level decision feedback. By overlaying virtual graphics on endoscopic pictures from the intraoperative stage, AR gives visual feedback to operating surgeons.^[195] Katic et al. suggested building a scaled 3-D model of the operational environment and calculating posture parameters of video collection from cameras concerning the CT scan coordinate frame.^[213] Another study used AR to produce motion-stabilized images of the heart which subsequently supported surgeons in performing surgical tasks with greater accuracy and repeatability.^[216] To date, many intuitive medical AR/MR devices have been used as a part of the user interface of TSRS including HoloLens, HoloLens 2, HoloLens IVAS CS3, Magic Leap

1, Meta 2, Epson Moverio BT300, Google Glass, or Vizux M400. Details on these technologies can be found in.^[217]

Tool detection, tissue tracking, and pose estimation created by endoscopic videos have also been used for giving context-specific feedback to the surgeon. Agustinos et al. developed an algorithm for tool detection and autonomous camera positioning via laparoscopic images, allowing the operating surgeon to have a better view of the operating region.^[218] Ryden et al. created a tool tracking program that provided estimated force information to prevent the surgeon from accessing a prohibited area such as a blood artery.^[219] To minimize the cognitive strain on the operating surgeon, Kehoe et al. employed tool pose estimation for the autonomous performance of some of the repetitive tasks in surgery such as debridement.^[220] Speaking of the SLAM approach, the performance of image-guided operations in TSRSs by this since it can supply the surgeons with extra geometric information about the surgical areas as an AI assistance. Chen et al., for example, proposed a unique intraoperative dense surface reconstruction framework for dealing with monocular MIS surgical scenarios by extending the state-of-the-art SLAM algorithm used in robotics with AR technology. This method can provide the surgeon with real-time 3D geometric information such as site measurement and depth cues through the user interface.^[221] As a result, the user interface in TSRSs becomes more intuitive potentially increasing the operational effectiveness. However, the use of SLAM can be difficult in more dynamic surgical environments.^[222] In reality, the surgical environment is frequently texture-free, and therefore it is important to monitor motion across time using data from the complete picture.^[223]

To equip the surgical systems with advanced control features, machine learning (ML) uses a set of algorithms to allow computers to learn directly from data of preprogrammed equations to subsequently analyze “big data” from surgical procedures. This technology offers surgeons excellent supporting equipment for vision technology to cope with the voluminous data of clinical parameters, surgical videos, and pathological images. It can be also applied as a tool for vision technology in surgical practice in the preoperative and intraoperative phases to assist surgeons in making appropriate decisions.^[224] The most frequent form of image processing method is the convolutional neural network (CNN) which is used to analyze data from endoscopy,

ultrasonography, CT, and MRI to locate primary cancers and metastatic regions.^[225] In the intraoperative phase, ML can provide automated intraoperative support and real-time cognition guidance. On intraoperative videos, for example, ML models are trained to produce generic rules applied to new data using unsupervised techniques.^[226] Furthermore, ML has been used to produce the automated identification of instruments, gestures, phrases, and anatomy, which is critical for comprehending surgery and providing helpful information for surgeons.^[227] Expanding its footprint in the clinical practice of surgery, ML is the fundamental tool of vision technology to meaningfully help surgeons with much better support.

7. Discussion and Conclusion

During the last few decades, the growing use of teleoperated surgical robotic platforms for MIS procedures has led to significant progress, enabling the transition from open surgery to surgical operations assisted by TSRSs as well as isolating surgeons away from radiation exposure. As technology develops and patents expire, robotic surgical systems become cheaper, smaller, and faster with available devices continuing to shrink in size and become more procedure specific.^[8] However, the success of robotic surgery is equally dependent on the surgeon's ability to communicate effectively with the robotic equipment. Given the telepresence requirements, this becomes more complicated in the case of the TSRS. Therefore, human factors must be considered during the development of any TSRSs. In this regard, the user interface or the master console of the TSRS should be further developed to provide surgeons with adequate information and effective control.^[4] One of the desired technologies required in TSRS is the need to integrate real-time haptic feedback through ergonomically enhanced wearable devices with smart textiles. Improved visual displays with advanced vision sensing technologies in the operating sites, accurate motion tracking/detecting technologies, and greater precision of surgical tools are other factors that need to be addressed.

Haptic feedback has been shown to significantly improve the performance of the surgeon in more complicated surgical tasks.^[228] Several factors must be considered to be able to offer reliable, precise, and intuitive haptic feedback information to optimize surgeon performance. They include sensing technologies for surgical instruments, feedback device actuation technologies, and wearable feedback-enabled smart garments.^[20] While actuation technology is now significantly improved with standard and new types of actuators,^[111] the two other areas are yet to achieve maturity. Although sensor-based force-sensing technologies using innovative artificial materials such as FBG^[229] or microfluidic-based sensors^[106] are promising, they still need to be developed in terms of overcoming millimeter-scale size limits, soft tissue features, accessibility challenges, and sterilization requirements. Meanwhile, the fabrication of novel wearable devices using smart garments is appropriate for use in a variety of body parts with varying levels of wearability^[145] and promises to deliver diverse types of feedback for a wide range of applications. Future developments in this rapidly growing field will improve the safety, reliability, and efficiency of the TSRS master consoles. However, the proliferation of new sensing and feedback devices and mechanisms, on the one hand, and the lack of widely ac-

knowledge systematic validation procedures, on the other hand, may stymie the adoption of new devices and techniques in clinical settings.^[25]

Motion tracking/detecting systems at the master console also play an important role in optimal TSRSs. It is vital to achieve reliable control algorithms between the master console and slave manipulator as the remote robotic tools will precisely follow the commands from the operator to complete the surgical operations with high efficiency. To date, the technologies used for motion tracking are still in an early stage of development with a few positive results from the commercially accessible sensors including position sensors, IMU sensors, and eye-tracking sensors. Similar to vision technologies, the sensing fusion employed for motion tracking is expected to provide more accurate results and enhance the human–robot interaction of the TSRS.

Current surgical vision displays can be perceived by the surgeon at the master console site. The information is directly provided by the real-time feed of the modular/stereo camera or indirectly from CT, MRI, and ultrasound technologies.^[230] The surgeon can now receive more imaging data through the application of visual sensing fusion technologies, which combine two or more vision technologies.^[206] Furthermore, the rich imaging data from these technologies have been processed and improved by using advanced technologies of AR, SLAM, and ML methods. As a result, surgeons have been supported better during the intraoperative phase of procedures with reliable tool detection, tracking, pose estimation, 3D mapping curves of surrounding tissues, and precise prediction of the camera position between frames. Other factors that contributed to these supports include real-time cognition guidance and automated identification of instruments, gestures, phases, and anatomy. Therefore, future master consoles should integrate advanced vision sensing fusion, augmented and mixed reality solutions, SLAM, and ML with visual feedback information.^[26]

The safety and feasibility of the TSRS's useable master console are the most important considerations. For most TSRS in surgical operations, safety is a major factor that must be addressed to obtain widespread acceptance.^[1] Although TSRSs have been established and validated in several clinical studies, there are still risks and uncertainties associated with the devices at the master console. This might be due to a lack of tactile feedback, resulting in incorrect assessment and damage to tissues and organs of patients, or nonergonomic wearable device designs, which could result in injuries to surgeons. Meanwhile, studies have compared the TSRS's technologies to traditional approaches to determine the viability of implementing it with a unique user interface in current practice or simulation settings. For example, Friedrich et al. showed that the Flex system which provides haptic and tactile feedback outperforms the traditional DaVinci system in several aspects.^[231] Another important impediment to the widespread use of TSRS in clinical practice is the high cost of purchasing and maintaining the systems. For example, in the USA, a new TSRS must eventually be examined and authorized by the US FDA through the 510(k) procedure to be sold commercially. Any new TSRSs are classed as high-risk devices that must go through the most stringent premarket approval (PMA) process. From the first communication through market deployment, a PMA device costs an average of \$94 million and takes 54 months.^[232]

Since surgeons and surgical teams are important factors in TSRSs, they are highly required to have a particular degree of training. In addition, surgical training is one of the main tools that may allow surgeons to gain competency fast and increasing performance when using TSRSs.^[233] As such, surgical training should be included during the development of TSRS user interfaces. Kang et al., for example, demonstrated that a recurrent training regimen efficiently prepared rookie surgeons for robotic-skill mastery.^[234] There are currently three main curricula of surgical training consisting of online training, hands-on training, and simulation training. Among these, only simulation training programs such as Robotic Surgical Simulator (RoSS) and da Vinci Skills Simulators (dVSS) can provide learners with the experience of actual TSRSs. These surgical robotic simulators are equipped with a surgeon master console, a visualization system, and other necessary features.^[235] Therefore, all technologies related to surgeons, especially haptic feedback, should be developed for the advanced master consoles in teleoperated surgical training. According to Chua et al., the dynamics of the training modality influence force estimating abilities during teleoperation, with past haptic experience accessible if created under the same dynamics as the task.^[236] It is obvious that, when used and directed correctly, haptic-enabled instruction is an important adjunct to training, competency, and improved patient outcomes.^[228]

While completely autonomous surgical systems remain a pipe dream, for the time being, a semi-autonomous teleoperated robotic medical assistant is a possible substitute. In TSRSs, we envisage a system that achieves semiautonomy by sharing task execution between the robot and the human surgeon. The translation from TSRSs to semi-autonomous surgical systems is becoming clearer these days since numerous semi-autonomous systems can execute surgical tasks with limited human intervention.^[237] Hu et al.,^[238] for example, suggested a semiautonomous tumor ablation system that offers the operator a collection of potential execution plans. Once a strategy is chosen, the robot completes the task autonomously. Similarly, Opfermann et al.^[239] created a system for tumor resection in which the user is first asked to indicate the extraction locations of the tumor, and then this knowledge is used to execute the operation autonomously. However, many issues must be overcome in order to raise the level of autonomy in present surgical robotic systems. They include analyzing surrounding situations through the use of tactile/force and position feedback with imaging methods, developing a strategy to adapt to changing environments, and carrying out surgical operations.^[240] It is expected that enhanced technology in robot-oriented sensing and actuation would play an important role in increasing the autonomous degree of surgical systems.^[241] The development of user interfaces is also important in this translation, where high-tech sensors and intelligent algorithms are essential for recreating experienced surgeons' sensorimotor abilities.^[1]

In conclusion, the field of human–robot interaction in current and future TSRSs is expected to have a significant impact on general healthcare and surgical operations. Indicative of its potential is the fact that devices integrated into the user interface in TSRSs have been considered for a wide range of medical disciplines, which is apparent from this review. Future developments in this sector will require addressing specific clinical and technical issues following an interdisciplinary approach. In addition,

the involvement of surgeons in the TSRS development process, as well as a focus on clinical research, is essential for developing clinically focused solutions. The master consoles of TSRS face technological hurdles linked to four key enabling technologies: haptics, ergonomics, robotic manipulation, vision sensing, and AI assistance. Indeed, clinical acceptability will hinge on the TSRS' capacity to provide demonstrable advantages to the health-care system in terms of better clinical outcomes, operational efficiency, and cost-effectiveness. As a result, the basic technologies are projected to increase the safety and feasibility of using the human–robot interface in medical interventions.

Acknowledgements

This work was supported by the UNSW Scientia Fellowship (PS46197), Intuitive Surgical Technology Research Grant (RG204224), the SPHERE Frontiers Technology Clinical Academic Group (RG210207), and the UNSW Start-Up funding (PS58173). C.C.N., M.T.T., and T.T.H. thank the support of the Science and Technology scholarship Program for Overseas Study for Master's and Ph.D. degrees, VinUniversity, Vingroup, Vietnam.

Conflict of Interest

The authors declare no conflict of interest.

Keywords

haptics, human–robot interfaces, intelligent systems, master consoles, minimally invasive surgeries, robotic surgical systems, smart garments

Received: October 16, 2022
Revised: December 23, 2022
Published online: January 24, 2023

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