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Title page:

Prevalence of haptic feedback in robot-mediated surgery: a systematic review of literature.

Author names and departments, and postal addresses:

Amirabdollahian, Farshid, School of Computer Science, University of Hertfordshire, , UK

Livatino, Salvatore, School of Engineering, University of Hertfordshire, , UK

Vahedi, Behrad, School of Engineering, University of Hertfordshire, , UK

Gudipati, Radhika, School of Computer Science, University of Hertfordshire, , UK

Sheen, Patrick, School of Engineering, University of Hertfordshire, UK

Gawrie-Mohan, Shan, Department of Anaesthetics, Lister Hospital, Stevenage, UK

Vasdev Nikhil, Hertfordshire and Bedfordshire Urological Cancer Centre, Department of Urology, Lister Hospital, Stevenage, UK AND School of Life and Medical Sciences, University of Hertfordshire, UK

1- Name and postal address of corresponding author:

Corresponding author: *Amirabdollahian, Farshid,

School of Computer Science, University of Hertfordshire, AL10 9AB, UK

Email: f.amirabdollahian2@herts.ac.uk

Tel: +44 1707 286 125

Fax: +44 1707 284 303

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Prevalence of haptic feedback in robot-mediated surgery: a systematic review of literature.

Amirabdollahian, Farshid; Livatino, Salvatore; Vahedi, Behrad; Gudipati, Radhika; Sheen, Patrick; Gawrie-Mohan, Shan; and Vasdev, Nikhil

Abstract

Background:

With the successful uptake and inclusion of robotic systems in minimally invasive surgery and with the increasing application of Robotic Surgery (RS) in numerous surgical specialities worldwide, there is now a need to develop and enhanced the technology further. One such improvement is the implementation and amalgamation of haptic feedback technology into RS which will permit the operating surgeon on the console to receive haptic information on the type of tissue being operated on. The main advantage of using this is to allow the operating surgeon to feel and control the amount of force applied to different tissues during surgery thus minimising the risk of using excessive force on tissue being used and hence reducing the risk of tissue damage due to both the direct and indirect effects of excessive tissue force or tension being applied during RS.

Method:

We performed a two-rater systematic review to identify the latest developments and potential avenues of improving technology in the application and implementation of haptic feedback technology to the operating surgeon on the console during RS. This review provides a summary of technological enhancements in RS, considering different stages of work, from proof of concept to cadaver tissue testing, surgery in animals and finally real implementation in surgical practice.

Results:

We identify that at the time of this review, while there is a unanimous agreement regarding need for haptic and tactile feedback, there are no solutions or products available that address this need.

Conclusions:

There is a scope and need for new developments in haptic augmentation for robot-mediated surgery with the aim of improving patient care and Robotic Surgical technology further.

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1 Introduction

Robotic Surgery is transforming minimally invasive surgery (MIS). A major issue currently with the expansion of Robotic Surgery is the complete lack of sensory information from the operative field to the operating robotic surgeon on the console. [1]. The complete absence of touch or haptic feedback to the operating surgeon on the robotic console has disadvantages on the elimination of force and tactile cues [2]. It has been shown that the lack of haptic feedback during robotic surgery results in unnecessary excessive or in certain circumstances lack of force being used during robotic surgery that results in damage to tissue or slipping of tissues during surgery [2]. We present a systematic review on the latest developments on robotic surgery and concomitant development of haptic feedback in different surgical specialities. Our goal is to assess the latest developments before embarking on formulating a haptic solution in a new collaboration. Next section introduces our methodology, while section 3 presents the result of our analysis followed by the discussion and conclusion (section 4).

2 Methodology

This systematic review aims to identify if any surgical robotic systems is used with additional augmentation of haptic and tactile sensing. Our study surveyed the “robot surgery + haptic” as search term with the PubMed to identify studies conducted in this area. The methodology used is adapted from [3, 4], consisting of 4 phases: identification, screening, eligibility and inclusion.

At the identification phase, two independent researchers used the search term in a PubMed search in November 2015. This resulted in identifying 138 records. An extra 3 unique records were identified after considering the references and also conducting a similar search with Web of Science and removing duplicate results. This led to a total of 141 studies in the screening phase. At this stage, the full abstract of all records were studied in order to rank the studies for relevance. The rank ranged from 1-5, 1 referring to least relevant and 5 referring to most relevant. A number of features were listed to aid in rank assignment, namely inclusion of a haptics or tactile device, its description, its interface, its degrees of freedom, and task dimensionality, as well as its intended type of operation, and whether the chosen approach has been tried on patients. These features were intended to provide input for the synthesis part of this work. As a concise search term was chosen, all articles in the screening list were passed to the eligibility check.

However, the researchers could not access the full text of 16 articles. These articles were unavailable at the University’s library, the British Library and the University College London (UCL) Library. Due to this, a decision was made to exclude these papers as it was not possible to completely evaluate them.

Both researchers read the full papers available during phase 3 (n = 125), and completed the ranking and also classification of each article within the list. The classification task consisted of filling in the details of the following features:

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- Haptic (yes or no)
- Probe type/interface (text)
- Speciality (text, e.g. robot-assisted surgery or more specific area of use)
- Adaptability (text, e.g. can it take new tools or tooltips)
- Haptic loop (text, e.g. if the article explains how virtual objects are rendered)
- Degree of freedom (text, related to degree of freedom for the surgeon)
- Task dimension (text, related to the degree of freedom at the probe)
- Tactile feedback (yes or no)
- Unimanual or bimanual (Unimanual or bimanual)
- Tried on patients (yes or no)
- Use type (One of the four choices: simulation, patient, cadaver, or animals)
- Hazard analysis (yes or no, e.g. is there any hazard analysis results provided)
- Additional notes (text)

After this process, the rating offered by the researchers were compared and the two raters met and discussed the differences. The researchers reached an agreement for all the scores given. Considering that a rank ≥ 3 indicated a relevant or highly relevant article, a total of 74 articles were selected and included in the next phase of the study.

The Table 1 summarises the process and the number of studies meeting the requirements during different phases of the review, while Table 2 presents the distribution of studies in different ranked groups.

During the next stages of evaluation, in subsequent sections, articles are fully read by co-authors, and their references and citations are examined, to identify new studies up to May 2017, that could include new developments in haptic for robotic surgery.

3 Results and Analysis

Results discussed in this section of the paper concerns the phase 4 results for studies with a rank greater or equal to 3 in ranking. Table 3 summarises these findings by grouping studies with attributes such as haptics, tactile, score, if the study is a review study and if patients were involved in the reviewed study. The following sections synthesise the observations under each of the table columns.

3.1 Haptics

Out of the 74 papers selected for further analysis (phase 4), 66 had referred to the word “haptics” somewhere in the article. This large number was expected as haptics was used as one of the search terms. Out of these, only a small number namely, [S116, S93] were identified as solutions tried on patients (see Table 4).

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Sutherland et al. [S116], present the potential for haptic enhancement using the neuroArm system where a haptic corridor is enabled to establish go and no-go areas in removal of glioma where brain shifts are apparent during the operation. The neuroArm surgical system links with two Omega 7 haptic devices that can provide a grasping force feedback of around 8N. The paper implies that this system is used to capture motion kinematics of the bipolar forces, during a real surgery in order to provide design requirements for the surgeon's haptic interface as detailed in subsequent publications [5, 6] where amount and range of interaction forces for a number of real glioma cases are presented.

Pearle et al. [S93], present clinical results from 10 clinical cases of using the unicompartmental knee arthroplasty (UKA) with the MAKO Tactile Guidance System. The study concludes that precision and alignment benefit from haptic and tactile augmentation, resulting in better operation results. However, the authors also point out that dependence on CT scans and regular costs for robotic maintenance are financial drawbacks, while complexity of setup in advance of sterile draping of the patient results in longer processes. Also they highlight that CT scans do not incorporate soft-tissue data into the gap planning and this is still done by manual flexion and extension intra operation.

3.1.1 Papers with a score of 5 in relevance

From the list of selected studies (in Table 3), those that have received a score of 5, as most relevant, are presented in Table 5 with description of studies and are considered for their contribution to haptics and its use in robot assisted surgery. Most shortlisted papers here provide design and evaluation of haptic technology for robot-mediated operation.

Diaz et al. [S24] consider using a haptic pedal for additional provision of tactile information during operation. PHANToM desktop has been used in this study as well as the haptic pedal. The study focused on reaction times that have been reduced when both tactile warning cues via the hand and foot have been deployed. However this approach has not been tested clinically and hence no further exploitation/use is found in additional literature search.

Ehrampoosh et al. [S26] use a PHANToM Omni with additional tooling to create tactile textures that can be detected during human-robot interaction. This study is a research study with the focus of identifying best control strategies to allow for better discrimination of the textures. Participants ranging 20-23 years old use the probe to detect real textures enclosed in a box. Study shows different levels of accuracy in detecting materials with different degrees of deformability. This approach has a good potential and has been followed up by another group showing a probe in real operation [7].

Study by Hadavand et al. [S34] covers the design of a 4 + 1 DOF robot that provides a feeling to the back of the surgeon's hand with a minimal moving inertia. The authors propose this as a solution to the Fulcrum effect that causes movements of the surgeon's hand and to tool tip to be in opposite directions, and aims at addressing this issue using the new design. The authors report

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issues with trajectory deviations due to backlash and vibrations which impacts on immediate use of this presented design in operations.

De Lorenzo et al. [S20] look at force feedback for needle insertion. This paper is a design paper for a 1DoF device with a specific tool in mind. It uses force amplification to bring attention to the forces at the tip of the needle. The work is still at proof of concept stage. However the innovation of tip and shaft force feedback could have potential use for design of other tools in this domain.

Hadavand et al. [S35] focus on designing a double parallelogram in order to shift the remote centre of motion and allow the surgeon's hand free movement as if it is inside the patient body, thus providing a more realistic remote access to the patient body. Although the design has progressed beyond the proof of concept stage in subsequent evolutions of this work [8], authors have reported errors in trajectory tracking attributed to backlash, and have not yet provided experimental evaluation data in support of further incorporating this design as a remote interaction tool for a minimally invasive operation mediated by a robot.

Work presented by Sun et al. [S115], highlights design and evaluation effort for a master robot used in natural orifice transluminal endoscopic surgery, presented to operate on live pigs during dissection and resection operation. The comparative results showed reduction of operation time by around 2 minutes using tooling offered in this design, compared to the current standard tooling, while presenting good stable grasping and cutting efficiency. However, subsequent evolution of the master robot for use with human subjects has not been presented in this or following studies by the authors. In similar endoscopic surgery domain, Tavakoli et al. [S121] presented design and development work surrounding a master- slave prototype, focusing on force-reflective features of platform. There were no follow up studies to show advantage of the platform in performing master-slave operations. In another study, Lee et al. [S60] present the development of their robot using sensors to provide a reliable force feedback in the context of laparoscopic surgery. The master- slave setup capable of 5DOF motion uses torque sensors in the pitch joints of the master and slave robots thus allowing to pass interaction forces to the master robot. However, further experiments showed limited level of subject discrimination when exploring objects. In an innovative approach, authors in [S48, S49] use a pneumatic balloon tactile display to offer additional cues to the master control of the Da Vinci robot. Design was followed by perception experiments identifying the optimal size for the balloon to offer highest accuracy.

Study by Shapiro et al. [S111] focuses on a bone-mounted robot for orthopaedic surgery. Such technologies are thought to provide support for intraoperative joint-surface reconstruction. The study is focused on exploring the feasibility of using haptics to feel and scan joint surfaces, in this case from a femur model of the bone. Results are compared to 3D laser scan of the femur bone, and presented in support of the feasibility of the haptics system. In comparison with earlier studies, this study adds a modelling dimension to the operation allowing to match the bone surface to an implant.

Work presented by Houston et al. [S38] highlights development of a haptic tweezers as an instrument added to the end of an endoscope. This study is focused on design of the tool and

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does not offer experiment results with patients or performance tests results regarding improvement to operation and handling time.

Research and development activities during the NeuroArm project resulted in a master- slave robotics system with a haptic interface [S105]. The haptic interface designed is in shape of a forceps with ergonomic design considerations. While this study covers the design of the device, no follow-up experiments are offered to highlight usability, and operational features of the haptic device, and its added value. Follow up studies with some of the authors explore the use of the master-slave platform, the NeuroArm robot, with new bipolar forceps in neurosurgical treatment of glioma [S116].

3.1.2 Papers with a scores of 3 and 4 in relevance

Considering the papers with a scores of 3 and 4, respectively, 34 and 26 studies are selected as relevant to the search terms (see Table 6). From these, only one study, mentioned previously, is used with patients [S116] without an actual focus on haptics use in operation. A number of studies used cadaver [S97] and animal body parts [S97, S94, S140] in suitability experiments. One study used healthy subjects for perceptual studies related to haptic discrimination [S141]. These are highlighted under “Tried On” column in Table 6, showing where the studies have tried their development. The majority of these studies have used the robotic intervention or the developed haptic tooling in simulation. Figure 1 presents the number of studies in different stages of development. This indicates the relative early stage of development for prototypes introduced. However, the large number of haptic developments for simulation highlight the necessity for having haptic tooling, for both education as well as augmenting senses during operation.

3.2 Tactile

Out of the 74 papers there were 6 papers classified after the feature Tactile Feedback (Table 7). Twenty-seven further papers were identified after considering the references.
We observe that current surgical robotic systems, including those for RMIS as in the da Vinci, have not yet integrated haptic and tactile feedback between instruments and tissue during surgery, while effectiveness of proposed solutions have only been tested in mock surgical tasks [S4, S61, S85]. These have mainly involved synthetic tissue models [S87, S75] and ex-vivo tissues [S94]. Attention has been put on both Touch (kinaesthetic) and Tactile (cutaneous) perception, which can be provided through haptic devices (grounded and body-based, [S75]), with tactile feedback appearing still far from practical adoption in tele-manipulation robots [S61]. Researchers have focused on both sensing and rendering [S61, 9] with the first one resulting more challenging [S61, S85].

Some of the experimentations of tactile feedback ran on commercial systems [S110], while others used these systems augmented with ad-hoc built prototypes [S87, S75, S94, S48]. All those systems had been proposed to perform palpation through cutaneous feedback.

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Some authors have proposed customized devices capable of displaying cutaneous feed- back, e.g. [10], [11], [12], and most recently attention has been paid to small wearable devices [13].
Minamizawa et al. [14] and Tsagarakis et al. [15] propose similar wearable devices relying on fingertip deformation and stretch, to simulate perception of objects' weight by displaying 2-DOFs (normal and lateral directions). However, their systems cannot provide forces in pointing direction which limits application to a number of grasping actions. The limitation is overcome in systems that are less portable, e.g. the wearable tactile device proposed by Solazzi et al. [16] that features motors placed on useŕs forearm and the presence of cables to convey motor torque.

Bau et al [17] propose a system to display cutaneous sensation to fingers through a touch screen when applying an underneath conductive layer reacting to voltages and therefore providing different friction forces when voltages alternate. Kuchenbecher [18] propose a similar system that brings display friction forces based on vibrations generated by the remote tools when a contact is present. Tezuka et al. [19] propose a new tactile device that consists of an array of needle-type electrodes that independently activate and provide this way a sensation of roughness or smoothness. They experimented effectiveness of the multi-needle shape and demonstrated that different types of tactile sensation can be provided on the finger and with much less voltage than other shapes.

Some authors focused on developing new devices. King et al. [S48] propose a tactile display system that provides cutaneous feedback through pneumatic balloons [20]. They ran experiments on a da Vinci console to assess the response for different balloons diameters, which resulted in the selection of optimal balloon diameters that provide maximum accuracy. A few other authors also proposedcustomized cutaneous feedback devices, [21], [22], [23], [24].

Some authors assess advantages of such systems within different MIS contexts.
Meli et al. [S75] assess the advantages of cutaneous feedback compared to having it coupled to kinaesthetic feedback, and also compared to auditory and visual feed- backs. They used a customized cutaneous feedback device (based on [23]) mounted on two grounded X Omega 7 haptic devices. In absence of delays the best results were obtained with a complete haptic feedback while cutaneous feedback was the second best. In presence of delays, cutaneous feedback only outperformed all other forms of feedback, by containing oscillations and therefore being more stable.

Pacchierotti et al. [S87] propose a novel system that provides feedback at finger-tip through deformation and vibration. The prototype system built on da Vinci end effector was composed by a commercially available tactile sensor (at the operating table) and custom cutaneous feedback device (at the surgeon's fingers). Experiments were carried out with and without haptic feedback and resulted in a significantly higher performance when the feedback was present.
Perri et al. [S94] proposed a laparoscopic system setup that provided feedback to surgeon's hand through a probe handle connected to a tactile sensing system (TSS) with capacity-based pressure sensor [25], [26]. The system included a visualization interface.

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Its performance was compared to MIS grippers such as an endoscopic grasper and a laparoscopic ultra-sound probe [S94]. The results were positive with a performance increase of up to 71%. Tactile feedback may or may not be coupled to touch feedback. Pacchierotti et al. [23] investigate decoupling cutaneous and kinaesthetic channels, modulating cutaneous force to compensate for a lack of kinaesthesia. They run an experiment where users were asked to perform a 1-DoF teleoperation task typical in key-hole surgery until a stiff constraint would be perceived. Better performance was achieved when cutaneous feedback was present to compensate the lack of kinaesthetic force, while over-actuated cutaneous forces performed even better. This work shows effectiveness of cutaneous feedback with the proposed tactile device.

Minamizawa, Prattichizzo and Tachi [27] propose a simplify haptic display that integrates tactile feedback on fingers and kinaesthetic feedback on an arm. They examine the difference of weight recognition according to the applied point of kinaesthetic feedback and come up with a design principle that confirms effectiveness of the proposed method.

Tactile feedback is inherently coupled to visual feedback. Some authors have included visual-tactile feedback in their experiments, e.g. to assess cutaneous only versus cutaneous plus kinaesthetic feedback [S75], or to assess the advantage of a probe-handle tactile feedback versus ultra-sound based probes [S94].

Segul et al. [S110] instead focus on assessing congruency between visual and tactile feedback. Experiments involved active and passive use of a virtual tool driven by a robot through visuo-tactile feedback. Both active and passive uses obtained similar results. The experiments showed that haptic devices can substitute physical connection between master and slave spaces, and therefore tele-manipulators consisting of haptic devices and virtual reality can be used in cognitive neuroscience investigations.

3.3 Type of Probe/Interface used

Another aspect of assessment was to consider use of different robotic platform at different stages of development in commercial life. Table 8 presents list of platforms identified as used in different studies. The table highlights that PHANToM robot (Geomagic ™) and the da Vinci Surgical systems are the most used platforms, followed by the Robocast system, while other platforms are at entry level, all with one study. Looking in particular for tools invented for extending Da Vinci robot, two studies highlighted present tools [S112, S87] used in simulation experiments, without any developments closer to market.

3.4 Surgical Speciality

Looking at the selected study paper, one aspect of the review is with regards to the specific surgical domain in which the devices are used. Table 4 list the studies based on their special surgical domains.

The table highlights that General Surgery and Gasterenterology have the largest of the recorded uses based on the current study. The development and introduction of haptic feedback will be of great benefit in both paediatric and adult patients. The technology will also benefit all patients from different specialities such as Urology, General Surgery, ENT surgery and cardiac surgery. The technology will also offer improvement in the manipulation of fragile specific tissue such as veins and arteries during surgery in order to prevent unnecessary damage to these structures intraoperative. Haptic feedback development will improve surgical training and precision of surgery further [28].

4 Discussions and Conclusions

This study considered existing literature around surgery tools with haptic augmentation. From a choice of classification features, haptics, tactile, involvement of patients and type of interface had sufficient information for further synthesis.

Our results highlight that although a large number of studies exist that consider haptics technology for augmenting the robot-mediated surgery, a large majority of these studies do not pass the early stages of design and developments, leading to higher technological readiness levels that allows for their evaluation in a real intended context for use, e.g. in a real surgical situation. This is further evident by very small number of studies that provide solutions for the Da Vinci Robot, while another small group continue to use PHANToM robot for simulation and further understanding of the context of interaction and user perception. A large proportion of the 74 studies included in this synthesis present developed tooling for the haptic augmentation, while majority of these studies do not progress into clinical experimentation during real surgery. Only a very small subset of these advance into a stage of cadaver or animal tissue manipulation. This is clearly presented in Figure 1 where number of studies shrink from simulation stage to animal testing and finally cadaver and patient tests.

When looking at the various systems that have been proposed for tactile feedback, it appears the technology has not consolidated yet. We observe that most of the contributions are based on individual hardware solutions and pilot assessments, and these often target specific subject areas. The proposed works are indeed inspiring but there is a feeling that more creative solutions may be needed to produce effective feedback while more generalised hardware would be needed for fast market adoption.

Also by comparing between Tables 5, 6 and 7, we can observe that majority of research consider kinaesthetic feedback (Tables 5 and 6), with a smaller number of the studies covering the tactile feedback (Table 7). This could be due to the relative maturity of haptics and robotics end-effectors that support kinaesthetic feedback versus a smaller number of technologies and tools that have provided support to tactile feedback at fingertips.

From clinical perspective, almost all of the shortlisted studies highlight the importance of additional cues to compensate for the loss of direct sensing, kinaesthetic or tactile. However, in the process of development, majority of these studies are stopped at early stage of the technological development. This could be due to a number of factors:

(a) The development required to provide a rich enough haptic feeling at the remote (master) site is bound to the limits of what today's technology can provide, and even with scaling the master site to 3 or 4 times larger scale than the operation site, current approaches do not manage to integrate both tactile and kinaesthetic senses, as well as the surgical task needs.

(b) A number of innovative solutions emerge that offer a combination of modalities, to offer stiffness or viscous feeling when dealing with different tissues. Yet we remain as relative novelty of tissue characterisation using visual or tactile interaction, and are furthermore limited by our ability to simulate the characterised tissues in a good enough form that it can be perceived as intended in its simulation.

(c) Studies that break through the first two barriers find a further challenge ahead related to regulations surrounding use of robotic tool in real-operation, or even within animal operation. These regulations, while necessary, reduce the ability to rapidly develop and iterate, while certification process for use within the intended environment is also a lengthy process and a costly endeavour.

When looking at technological deployment within different surgical specialism, we can see that the technology is expanding its use in different specialisms, with general surgery and gasterenterology as most popular and widely used domains.

This study provides the initial input for our planned development work, in designing a haptic interface for augmenting the surgical robotic interventions. The initial findings suggest that although most studies agree with the ”need”, the need is unmet in current available technologies, thus there exist a clear problem that can benefit and enhance our surgical tools.
Authors involved in this study are part of the team embarking on a new design challenge to meet the need, while benefitting from this literature, as well as daily surgical experience of Mr Nikhil Vasdev and Mr Gawrie-Mohan.

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6 Conflict of Interest

All authors declare that they no conflict of interest.

7 Informed Consent

This study did not involve any human subjects.

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References

[1] Ehrampoosh Shervin, Dave Mohit, Kia Michael A, Rablau Corneliu, Zadeh Mehrdad H. Providing haptic feedback in robot-assisted minimally invasive surgery: A direct optical force-sensing solution for haptic rendering of deformable bodies Com- puter Aided Surgery. 2013;18:129–141.

[2] Akinbiyi Takintope, Reiley Carol E, Saha Sunipa, et al. Dynamic augmented reality for sensory substitution in robot-assisted surgical systems in Engineering in Medicine and Biology Society, 2006. EMBS'06. 28th Annual International Conference of the IEEE:567–570IEEE 2006.

[3] Autorino Riccardo, Kaouk Jihad H., Stolzenburg Jens-Uwe, et al. Current Status and Future Directions of Robotic Single-Site Surgery: A Systematic Review European Urology. 2013;63:266 - 280.

[4] Liberati Alessandro, Altman Douglas G, Tetzlaff Jennifer, et al. The PRISMA state- ment for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration Annals of internal medicine. 2009;151:W–65.

[5] Maddahi Yaser, Ghasemloonia Ahmad, Zareinia Kourosh, Sepehri Nariman, Suther- land Garnette R. Quantifying force and positional frequency bands in neurosurgical tasks Journal of robotic surgery. 2016;10:97–102.

[6] Maddahi Yaser, Zareinia Kourosh, Gan Liu Shi, Sutherland Christina, Lama Sanju, Sutherland Garnette R. Treatment of Glioma Using neuroArm Surgical System BioMed Research International. 2016;2016.

[7] Solodova Rozalia F, Galatenko Vladimir V, Nakashidze Eldar R, et al. instrumen- tal tactile diagnostics in robot-assisted surgery Medical Devices (Auckland, NZ). 2016;9:377.

[8] Hadavand Mostafa, Mirbagheri Alireza, Behzadipour Saeed, Farahmand Farzam. A novel remote center of motion mechanism for the force-reflective master robot of haptic tele-surgery systems The International Journal of Medical Robotics and Computer Assisted Surgery. 2014;10:129–139.

[9] Craig James C. Tactile pattern perception and its perturbations The Journal of the Acoustical Society of America. 1985;77:238–246.

[10] Watanabe Toshio, Fukui Shigehisa. A method for controlling tactile sensation of surface roughness using ultrasonic vibration in Robotics and Automation, 1995. Pro- ceedings., 1995 IEEE International Conference on;1:1134–1139IEEE 1995.

[11] Takasaki Masaya, Nara Takaaki, Tachi Susumu, Higuchi Toshiro. A tactile display using surface acoustic wave in Robot and Human Interactive Communication, 2000. RO- MAN 2000. Proceedings. 9th IEEE International Workshop on:364–367IEEE 2000.

[12] Ikei Yasushi, Wakamatsu Kazufumi, Fukuda Shuichi. Texture presentation by vibra- tory tactile display-image based presentation of a tactile texture in Virtual Reality Annual International Symposium, 1997., IEEE 1997:199–205IEEE 1997.

[13] Benali-Khoudja Mohamed, Hafez Moustapha, Alexandre Jean-Marc, Kheddar Ab- derrahmane. Tactile interfaces: a state-of-the-art survey in Int. Symposium on Robotics;31:23–26Citeseer 2004.

[14] Minamizawa Kouta, Fukamachi Souichiro, Kajimoto Hiroyuki, Kawakami Naoki, Tachi Susumu. Gravity grabber: wearable haptic display to present virtual mass sen- sation in ACM SIGGRAPH 2007 emerging technologies:8ACM 2007.

[15] Tsagarakis Nikolaos G, Horne T, Caldwell Darwin G. Slip aestheasis: A portable 2d slip/skin stretch display for the fingertip in Eurohaptics Conference, 2005 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2005. World Haptics 2005. First Joint:214–219IEEE 2005.

[16] Solazzi Massimiliano, Frisoli Antonio, Bergamasco Massimo. Design of a cutaneous fingertip display for improving haptic exploration of virtual objects in RO-MAN, 2010 IEEE:1–6IEEE 2010.

[17] Bau Olivier, Poupyrev Ivan, Israr Ali, Harrison Chris. TeslaTouch: electrovibration for touch surfaces in Proceedings of the 23nd annual ACM symposium on User interface software and technology:283–292ACM 2010.

[18] Kuchenbecker Katherine, Gewirtz Jamie, McMahan William, et al. VerroTouch: high-frequency acceleration feedback for telerobotic surgery Haptics: Generating and perceiving tangible sensations. 2010:189–196.
[19] Tezuka Mayuko, Kitamura Norihide, Miki Norihisa. Micro-needle electro-tactile dis- play in Engineering in Medicine and Biology Society (EMBC), 2015 37th Annual International Conference of the IEEE:5781–5784IEEE 2015.
[20] King C, Higa Adrienne T, Culjat Martin O, et al. A pneumatic haptic feedback actuator array for robotic surgery or simulation Studies in health technology and in- formatics. 2006;125:217.
[21] Prattichizzo Domenico, Chinello Francesco, Pacchierotti Claudio, Malvezzi Monica. Towards wearability in fingertip haptics: a 3-dof wearable device for cutaneous force feedback IEEE Transactions on Haptics. 2013;6:506–516.
[22] Pacchierotti Claudio, Chinello Francesco, Malvezzi Monica, Meli Leonardo, Prat- tichizzo Domenico. Two finger grasping simulation with cutaneous and kinesthetic force feedback in International Conference on Human Haptic Sensing and Touch En- abled Computer Applications:373–382Springer 2012.
[23] Pacchierotti Claudio, Tirmizi Asad, Prattichizzo Domenico. Improving transparency in teleoperation by means of cutaneous tactile force feedback ACM Transactions on Applied Perception (TAP). 2014;11:4.
[24] Pacchierotti Claudio, Chinello Francesco, Prattichizzo Domenico. Cutaneous de- vice for teleoperated needle insertion in Biomedical Robotics and Biomechatronics (BioRob), 2012 4th IEEE RAS & EMBS International Conference on:32–37IEEE 2012.
[25] Fearing Ronald S. Tactile sensing mechanisms The International Journal of Robotics Research. 1990;9:3–23.
[26] Trejos Ana Luisa, Jayender Jagadeesan, Perri MT, Naish Michael D, Patel Ra- jnikant V, Malthaner RA. Robot-assisted tactile sensing for minimally invasive tumor localization The International Journal of Robotics Research. 2009;28:1118–1133.
[27] Minamizawa Kouta, Prattichizzo Domenico, Tachi Susumu. Simplified design of hap- tic display by extending one-point kinesthetic feedback to multipoint tactile feedback in Haptics Symposium, 2010 IEEE:257–260IEEE 2010.
[28] Vasdev Nikhil, Bishop Conrad, Kass-Iliyya Atoine, et al. Developing a robotic prosta- tectomy service and a robotic fellowship programme-defining the learning curve Cur- rent urology. 2013;7:136–144.
[29] Bowes D., Hall T., Beecham S.. SLuRp: A Tool to Help Large Complex System- atic Literature Reviews Deliver Valid and Rigorous Results in The 2nd International Workshop on Evidential Assessment of Software Technologies 2012.

Study Papers

[S1] Abolhassani N., Patel R. V.. Teleoperated master-slave needle insertion Int J Med Robot. 2009;5:398{405.
[S2] Advincula A. P., Song A.. The role of robotic surgery in gynecology Curr. Opin. Obstet. Gynecol.. 2007;19:331{336.
[S3] Akinbiyi T., Reiley C. E., Saha S., et al. Dynamic augmented reality for sensory substitution in robot-assisted surgical systems Conf Proc IEEE Eng Med Biol Soc. 2006;1:567{570.
[S4] Banerjee S., Cherian J. J., Elmallah R. K., Jauregui J. J., Pierce T. P., Mont M. A.. Robotic-assisted knee arthroplasty Expert Rev Med Devices. 2015;12:727{735.
[S5] Banks S. A.. Haptic robotics enable a systems approach to design of a minimally invasive modular knee arthroplasty Am J. Orthop.. 2009;38:23{27.
[S6] Bethea B. T., Okamura A. M., Kitagawa M., et al. Application of haptic feedback to robotic surgery J Laparoendosc Adv Surg Tech A. 2004;14:191{195.

[S7] Beyl T., Nicolai P., Monnich H., Raczkowksy J.,Worn H.. Haptic feedback in OP:Sense - augmented reality in telemanipulated robotic surgery Stud Health Technol Inform. 2012;173:58{63.
[S8] Bhattacharjee T., Son H. I., Lee D. Y.. Haptic control with environment force estimation for telesurgery Conf Proc IEEE Eng Med Biol Soc. 2008;2008:3241{3244.
[S9] Bianchi M., Gwilliam J. C., Degirmenci A., Okamura A. M.. Characterization of an air jet haptic lump display Conf Proc IEEE Eng Med Biol Soc. 2011;2011:3467{3470.
[S10] Bornhoft J. M., Strabala K. W., Wortman T. D., Lehman A. C., Oleynikov D., Farritor S. M.. Stereoscopic visualization and haptic technology used to create a virtual environment for remote surgery - biomed 2011 Biomed Sci Instrum. 2011;47:76{81.
[S11] Bowyer S. A., Rodriguez Y Baena F.. Deformation invariant bounding spheres for dynamic active constraints in surgery Proc Inst Mech Eng H. 2014;228:350{361.
[S12] Cabuk B., Ceylan S., Anik I., Tugasaygi M., Kizir S.. A Haptic Guided Robotic System for Endoscope Positioning and Holding Turk Neurosurg. 2015;25:601{607.
[S13] Cannon J. W., Howe R. D., Dupont P. E., Triedman J. K., Marx G. R., Nido P. J.. Application of robotics in congenital cardiac surgery Semin Thorac Cardiovasc Surg Pediatr Card Surg Annu. 2003;6:72{83.
[S14] Choi C., Kim J., Han H., Ahn B., Kim J.. Graphic and haptic modelling of the oesophagus for VR-based medical simulation Int J Med Robot. 2009;5:257{266.
[S15] Chowriappa A., Raza S. J., Fazili A., et al. Augmented-reality-based skills training for robot-assisted urethrovesical anastomosis: a multi-institutional randomised controlled trial BJU Int.. 2015;115:336{345.
[S16] Comparetti M. D., Vaccarella A., Dyagilev I., Shoham M., Ferrigno G., De Momi E.. Accurate multi-robot targeting for keyhole neurosurgery based on external sensor monitoring Proc Inst Mech Eng H. 2012;226:347{359.
[S17] Cruces R. A., Wahrburg J.. Improving robot arm control for safe and robust haptic cooperation in orthopaedic procedures Int J Med Robot. 2007;3:316{322.
[S18] Culmer P., Barrie J., Hewson R., et al. Reviewing the technological challenges associated with the development of a laparoscopic palpation device Int J Med Robot. 2012;8:146{159.
[S19] Cundy T. P., Gattas N. E., Yang G. Z., Darzi A., Najmaldin A. S.. Experience related factors compensate for haptic loss in robot-assisted laparoscopic surgery J. Endourol.. 2014;28:532{538.
[S20] De Lorenzo D., Koseki Y., De Momi E., Chinzei K., Okamura A. M.. Coaxial needle insertion assistant with enhanced force feedback IEEE Trans Biomed Eng. 2013;60:379{389.
[S21] De Lorenzo D., De Momi E., Dyagilev I., et al. Force feedback in a piezoelectric linear actuator for neurosurgery Int J Med Robot. 2011;7:268{275.
[S22] De Momi E., Ferrigno G.. Robotic and arti_cial intelligence for keyhole neurosurgery: the ROBOCAST project, a multi-modal autonomous path planner Proc Inst Mech Eng H. 2010;224:715{727.
[S23] Devarajan V., Wang X., Shen Y., et al. A novel laparoscopic mesh placement part task trainer Int J Med Robot. 2006;2:312{320.
[S24] Diaz I., Gil J. J., Louredo M.. A haptic pedal for surgery assistance Comput Methods Programs Biomed. 2014;116:97{104.
[S25] Val I., Loureiro C., McCulloch P.. The IDEAL prospective development study format for reporting surgical innovations. An illustrative case study of robotic oesophagectomy Int J Surg. 2015;19:104{111.
[S26] Ehrampoosh S., Dave M., Kia M. A., Rablau C., Zadeh M. H.. Providing haptic feedback in robot-assisted minimally invasive surgery: a direct optical force-sensing solution for haptic

rendering of deformable bodies Comput. Aided Surg.. 2013;18:129{141.
[S27] Falkenback D., Lehane C.W., Lord R. V.. Robot-assisted oesophageal and gastric surgery for benign disease: antireux operations and Heller's myotomy ANZ J Surg. 2015;85:113{120.
[S28] Fichera L., Pardo D., Illiano P., Ortiz J., Caldwell D. G., Mattos L. S.. Online estimation of laser incision depth for transoral microsurgery: approach and preliminary evaluation Int J Med Robot. 2016;12:53{61.
[S29] Freschi C., Ferrari V., Mel_ F., Ferrari M., Mosca F., Cuschieri A.. Technical review of the da Vinci surgical telemanipulator Int J Med Robot. 2013;9:396{406.
[S30] Fujiwara K., Fukuhara T., Niimi K., et al. Mechanical evaluation of newly developed mouth-piece using polyethylene terephthalate glycol for transoral robotic surgery J Robot Surg. 2015;9:347{354.
[S31] Fujiwara K., Fukuhara T., Niimi K., Sato T., Kitano H.. Load evaluation of the da Vinci surgical system for transoral robotic surgery J Robot Surg. 2015;9:315{319.
[S32] Gosling T., Westphal R., Hufner T., et al. Robot-assisted fracture reduction: a preliminary study in the femur shaft Med Biol Eng Comput. 2005;43:115{120.
[S33] Tholey Gregory, Chanthasopeephan Teeranoot, Hu Tie, Desai Jaydev P., Lau Alan. Measuring grasping and cutting forces for reality-based haptic modeling International Congress Series. 2003;1256:794 - 800. fCARSg 2003. Computer Assisted Radiology and Surgery. Proceedings of the 17th International Congress and Exhibition.
[S34] Hadavand M., Mirbagheri A., Behzadipour S., Farahmand F.. A novel remote center of motion mechanism for the force-reective master robot of haptic tele-surgery systems Int J Med Robot. 2014;10:129{139.
[S35] Hadavand M., Mirbagheri A., Salarieh H., Farahmand F.. Design of a force-reective master robot for haptic telesurgery applications: RoboMaster1 Conf Proc IEEE Eng Med Biol Soc. 2011;2011:7037{7040.
[S36] Hagen M. E., Meehan J. J., Inan I., Morel P.. Visual clues act as a substitute for haptic feedback in robotic surgery Surg Endosc. 2008;22:1505{1508.
[S37] Halic T., Sankaranarayanan G., De S.. GPU-based e_cient realistic techniques for bleeding and smoke generation in surgical simulators Int J Med Robot. 2010;6:431{443.
[S38] Houston K., Sieber A., Eder C., Tonet O., Menciassi A., Dario P.. Novel haptic tool and input device for real time bilateral biomanipulation addressing endoscopic surgery Conf Proc IEEE Eng Med Biol Soc. 2007;2007:198{201.
[S39] Hu T., Tholey G., Desai J. P., Castellanos A. E.. Evaluation of a laparoscopic grasper with force feedback Surg Endosc. 2004;18:863{867.
[S40] Hu Z., Sun W., Zhang B.. Characterization of aortic tissue cutting process: experimental investigation using porcine ascending aorta J Mech Behav Biomed Mater. 2013;18:81{89.
[S41] Huart A., Facca S., Lebailly F., Garcia J. C., Liverneaux P. A.. Are pedicled aps feasible in robotic surgery? Report of an anatomical study of the kite ap in conventional surgery versus robotic surgery Surg Innov. 2012;19:89{92.
[S42] Hughes-Hallett A., Mayer E. K., Marcus H. J., et al. Augmented reality partial nephrectomy: examining the current status and future perspectives Urology. 2014;83:266{273.
[S43] Jacob B. P., Gagner M.. Robotics and general surgery Surg. Clin. North Am.. 2003;83:1405{1419.
[S44] Johnson P. J., Schmidt D. E., Duvvuri U.. Output control of da Vinci surgical system's surgical graspers J. Surg. Res.. 2014;186:56{62.
[S45] Jung H., Lee D. Y., Ahn W.. Real-time deformation of colon and endoscope for colonoscopy simulation Int J Med Robot. 2012;8:273{281.
[S46] Katz R. D., Taylor J. A., Rosson G. D., Brown P. R., Singh N. K.. Robotics in plastic

and reconstructive surgery: use of a telemanipulator slave robot to perform microvascular anastomoses J Reconstr Microsurg. 2006;22:53{57.
[S47] Khan F., Pearle A., Lightcap C., Boland P. J., Healey J. H.. Haptic robot-assisted surgery improves accuracy of wide resection of bone tumors: a pilot study Clin. Orthop. Relat. Res.. 2013;471:851{859.
[S48] King C. H., Culjat M. O., Franco M. L., Bisley J. W., Dutson E., Grundfest W. S.. Optimization of a pneumatic balloon tactile display for robot-assisted surgery based on human perception IEEE Trans Biomed Eng. 2008;55:2593{2600.
[S49] King C. H., Higa A. T., Culjat M. O., et al. A pneumatic haptic feedback actuator array for robotic surgery or simulation Stud Health Technol Inform. 2007;125:217{222.
[S50] Kitagawa M., Dokko D., Okamura A. M., Yuh D. D.. E_ect of sensory substitution on suture-manipulation forces for robotic surgical systems J. Thorac. Cardiovasc. Surg.. 2005;129:151{158.
[S51] Kitagawa M., Dokko D., Okamura A. M., Bethea B. T., Yuh D. D.. E_ect of sensory substitution on suture manipulation forces for surgical teleoperation Stud Health Technol Inform. 2004;98:157{163.
[S52] Kobayashi Y., Moreira P., Liu C., Poignet P., Zemiti N., Fujie M. G.. Haptic feedback control in medical robots through fractional viscoelastic tissue model Conf Proc IEEE Eng Med Biol Soc. 2011;2011:6704{6708.
[S53] Koehn J. K., Kuchenbecker K. J.. Surgeons and non-surgeons prefer haptic feedback of instrument vibrations during robotic surgery Surg Endosc. 2015;29:2970{2983.
[S54] Kuang W., Shin P. R., Oder M., Thomas A. J.. Robotic-assisted vasovasostomy: a two-layer technique in an animal model Urology. 2005;65:811{814.
[S55] Kuang W., Shin P. R., Matin S., Thomas A. J.. Initial evaluation of robotic technology for microsurgical vasovasostomy J. Urol.. 2004;171:300{303.
[S56] Kumar R., Yadav R., Kolla S. B.. Simultaneous bilateral robot-assisted dismembered pyeloplasties for bilateral ureteropelvic junction obstruction: technique and literature review J. Endourol.. 2007;21:750{753.
[S57] Kwok K. W., Tsoi K. H., Vitiello V., et al. Dimensionality Reduction in Controlling Articulated Snake Robot for Endoscopy Under Dynamic Active Constraints IEEE Trans Robot. 2013;29:15{31.
[S58] Lang J. E., Mannava S., Floyd A. J., et al. Robotic systems in orthopaedic surgery J Bone Joint Surg Br. 2011;93:1296{1299.
[S59] Le Roux P. D., Das H., Esquenazi S., Kelly P. J.. Robot-assisted microsurgery: a feasibility study in the rat Neurosurgery. 2001;48:584{589.
[S60] Lee D. H., Choi J., Park J. W., et al. An implementation of sensor-based force feedback in a compact laparoscopic surgery robot ASAIO J.. 2009;55:83{85.
[S61] Lee S. L., Lerotic M., Vitiello V., et al. From medical images to minimally invasive intervention: Computer assistance for robotic surgery Comput Med Imaging Graph. 2010;34:33{45.
[S62] Li M., Konstantinova J., Secco E. L., et al. Using visual cues to enhance haptic feedback for palpation on virtual model of soft tissue Med Biol Eng Comput. 2015;53:1177{1186.
[S63] Li M., Liu H., Jiang A., et al. Intra-operative tumour localisation in robot-assisted minimally invasive surgery: A review Proc Inst Mech Eng H. 2014;228:509{522.
[S64] Li X., Gu L., Zhang S., et al. Hierarchical spatial hashing-based collision detection and hybrid collision response in a haptic surgery simulator Int J Med Robot. 2008;4:77{86.
[S65] Lim S. C., Lee H. K., Park J.. Role of combined tactile and kinesthetic feedback in minimally invasive surgery Int J Med Robot. 2014.
[S66] Liu J., Cramer S. C., Reinkensmeyer D. J.. Learning to perform a new movement with

robotic assistance: comparison of haptic guidance and visual demonstration J Neuroeng Rehabil. 2006;3:20.
[S67] Liu Y., Wang S., Hu S. J., Qiu W.. Mechanical analysis of end-to-end silk-sutured anastomosis for robot-assisted surgery Int J Med Robot. 2009;5:444{451.
[S68] Maciel A., Halic T., Lu Z., Nedel L. P., De S.. Using the PhysX engine for physics-based virtual surgery with force feedback Int J Med Robot. 2009;5:341{353.
[S69] Maciel A., Liu Y., Ahn W., Singh T. P., Dunnican W., De S.. Development of the VBLaST: a virtual basic laparoscopic skill trainer Int J Med Robot. 2008;4:131{138.
[S70] Maddahi Y., Gan L. S., Zareinia K., Lama S., Sepehri N., Sutherland G. R.. Quantifying workspace and forces of surgical dissection during robot-assisted neurosurgery Int J Med Robot. 2016;12:528{537.
[S71] Marcus H. J., Hughes-Hallett A., Cundy T. P., Yang G. Z., Darzi A., Nandi D.. da Vinci robot-assisted keyhole neurosurgery: a cadaver study on feasibility and safety Neurosurg Rev. 2015;38:367{371.
[S72] Marecik S. J., Prasad L. M., Park J. J., Jan A., Chaudhry V.. Evaluation of midlevel and upper-level residents performing their _rst robotic-sutured intestinal anastomosis Am. J. Surg.. 2008;195:333{337.
[S73] Masjedi M., Tan W. L., Jaskaranjit S., Aqil A., Harris S., Cobb J.. Use of robotic technology in cam femoroacetabular impingement corrective surgery Int J Med Robot. 2013;9:23{28.
[S74] McBeth P. B., Louw D. F., Rizun P. R., Sutherland G. R.. Robotics in neurosurgery Am. J. Surg.. 2004;188:68S-75S.
[S75] Meli L., Pacchierotti C., Prattichizzo D.. Sensory subtraction in robot-assisted surgery: _ngertip skin deformation feedback to ensure safety and improve transparency in bimanual haptic interaction IEEE Trans Biomed Eng. 2014;61:1318{1327.
[S76] Moglia A., Turini G., Ferrari V., Ferrari M., Mosca F.. Patient speci_c surgical simulator for the evaluation of the movability of bimanual robotic arms Stud Health Technol Inform. 2011;163:379{385.
[S77] Mohammadzadeh N., Safdari R.. Robotic surgery in cancer care: opportunities and challenges Asian Pac. J. Cancer Prev.. 2014;15:1081{1083.
[S78] Mojra A., Najarian S., Towliat Kashani S. M., Panahi F., Yaghmaei M.. A novel haptic robotic viscogram for characterizing the viscoelastic behaviour of breast tissue in clinical examinations Int J Med Robot. 2011;7:282{292.
[S79] Moscarelli M., Harling L., Ashra_an H., Athanasiou T., Casula R.. Challenges facing totally endoscopic robotic coronary artery bypass grafting Int J Med Robot. 2015;11:18{29.
[S80] Mozer P., Troccaz J., Stoianovici D.. Urologic robots and future directions Curr Opin Urol. 2009;19:114{119.
[S81] Mylonas G. P., Kwok K. W., James D. R., et al. Gaze-Contingent Motor Channelling, haptic constraints and associated cognitive demand for robotic MIS Med Image Anal. 2012;16:612{631.
[S82] Nawrat Z., Podsedkowski L., Mianowski K., et al. Robin Heart 2003{present state of the Polish telemanipulator project for cardiac surgery assistance Int J Artif Organs. 2003;26:1115{1119.
[S83] Nick A. M., Ramirez P. T.. The impact of robotic surgery on gynecologic oncology J Gynecol Oncol. 2011;22:196{202.
[S84] Ohnishi K., Shimono T., Natori K.. [Development of real-world haptic technology] Gan To Kagaku Ryoho. 2012;39:1035{1038.
[S85] Okamura A. M.. Haptic feedback in robot-assisted minimally invasive surgery Curr Opin Urol. 2009;19:102{107.

[S86] Okamura A. M.. Methods for haptic feedback in teleoperated robot-assisted surgery Ind Rob. 2004;31:499{508.
[S87] Pacchierotti C., Prattichizzo D., Kuchenbecker K. J.. Cutaneous Feedback of Fingertip Deformation and Vibration for Palpation in Robotic Surgery IEEE Trans Biomed Eng. 2016;63:278{287.
[S88] Pan J. J., Chang J., Yang X., et al. Virtual reality training and assessment in laparoscopic rectum surgery Int J Med Robot. 2015;11:194{209.
[S89] Pan J. J., Chang J., Yang X., et al. Graphic and haptic simulation system for virtual laparoscopic rectum surgery Int J Med Robot. 2011;7:304{317.
[S90] Park J. W., Choi J., Park Y., Sun K.. Haptic virtual _xture for robotic cardiac catheter navigation Artif Organs. 2011;35:1127{1131.
[S91] Park J. W., Choi J., Pak H. N., et al. Development of a force-reecting robotic platform for cardiac catheter navigation Artif Organs. 2010;34:1034{1039.
[S92] Paul L., Cartiaux O., Docquier P. L., Banse X.. Ergonomic evaluation of 3D plane positioning using a mouse and a haptic device Int J Med Robot. 2009;5:435{443.
[S93] Pearle A. D., O'Loughlin P. F., Kendo_ D. O.. Robot-assisted unicompartmental knee arthroplasty J Arthroplasty. 2010;25:230{237.
[S94] Perri M. T., Trejos A. L., Naish M. D., Patel R. V., Malthaner R. A.. New tactile sensing system for minimally invasive surgical tumour localization Int J Med Robot. 2010;6:211{220.
[S95] Perrier N. D., Randolph G. W., Inabnet W. B., Marple B. F., VanHeerden J., Kuppersmith R. B.. Robotic thyroidectomy: a framework for new technology assessment and safe implementation Thyroid. 2010;20:1327{1332.
[S96] Pisla D., Gherman B., Plitea N., et al. PARASURG hybrid parallel robot for minimally invasive surgery Chirurgia (Bucur). 2011;106:619{625.
[S97] Pisla D., Plitea N., Vaida C., et al. PARAMIS parallel robot for laparoscopic surgery Chirurgia (Bucur). 2010;105:677{683.
[S98] Pow-Sang J.. Pure and robotic-assisted laparoscopic radical prostatectomy: technology and techniques merge to improve outcomes Expert Rev Anticancer Ther. 2008;8:15{19.
[S99] Punak S., Kurenov S.. A simple master-slave control mapping setup to learn robot-assisted surgery manipulation Stud Health Technol Inform. 2012;173:356{358.
[S100] Rassweiler J., Sa_ K. C., Subotic S., Teber D., Frede T.. Robotics and telesurgery{an update on their position in laparoscopic radical prostatectomy Minim Invasive Ther Allied Technol. 2005;14:109{122.
[S101] Reiley C. E., Akinbiyi T., Burschka D., Chang D. C., Okamura A. M., Yuh D. D.. E_ects of visual force feedback on robot-assisted surgical task performance J. Thorac. Cardiovasc. Surg.. 2008;135:196{202.
[S102] Reilink R., Kappers A. M., Stramigioli S., Misra S.. Evaluation of robotically controlled advanced endoscopic instruments Int J Med Robot. 2013;9:240{246.
[S103] Reilink R., Stramigioli S., Kappers A.M., Misra S.. Evaluation of exible endoscope steering using haptic guidance Int J Med Robot. 2011;7:178{186.
[S104] Ricchiuti D., Cerone J., Shie S., Jetley A., Noe D., Kovacik M.. Diminished suture strength after robotic needle driver manipulation J. Endourol.. 2010;24:1509{1513.
[S105] Rizun P., Gunn D., Cox B., Sutherland G.. Mechatronic design of haptic forceps for robotic surgery Int J Med Robot. 2006;2:341{349.
[S106] Rossi A., Trevisani A., Zanotto V.. A telerobotic haptic system for minimally invasive stereotactic neurosurgery Int J Med Robot. 2005;1:64{75.
[S107] Sangpradit K., Liu H., Dasgupta P., Althoefer K., Seneviratne L. D.. Finite-element modeling of soft tissue rolling indentation IEEE Trans Biomed Eng. 2011;58:3319{3327.

[S108] Schneider C., Baghani A., Rohling R., Salcudean S.. Remote ultrasound palpation for robotic interventions using absolute elastography Med Image Comput Comput Assist Interv. 2012;15:42{49.
[S109] Seifabadi R., Iordachita I., Fichtinger G.. Design of a Teleoperated Needle Steering System for MRI-guided Prostate Interventions Proc IEEE RAS EMBS Int Conf Biomed Robot Biomechatron. 2012;2012:793{798.
[S110] Sengul A., Elk M., Rognini G., Aspell J. E., Bleuler H., Blanke O.. Extending the body to virtual tools using a robotic surgical interface: evidence from the crossmodal congruency task PLoS ONE. 2012;7:e49473.
[S111] Shapiro Y., Wolf A.. Introducing haptic capabilities to a bone-mounted robot for intraoperative surface scanning Int J Med Robot. 2010;6:444{453.
[S112] Shimachi S., Hirunyanitiwatna S., Fujiwara Y., Hashimoto A., Hakozaki Y.. Adapter for contact force sensing of the da Vinci robot Int J Med Robot. 2008;4:121{130.
[S113] Simorov A., Otte R. S., Kopietz C. M., Oleynikov D.. Review of surgical robotics user interface: what is the best way to control robotic surgery? Surg Endosc. 2012;26:2117{2125.
[S114] Son H. I., Bhattacharjee T., Lee D. Y.. Estimation of environmental force for the haptic interface of robotic surgery Int J Med Robot. 2010;6:221{230.
[S115] Sun Z., Ang R. Y., Lim E. W., Wang Z., Ho K. Y., Phee S. J.. Enhancement of a master-slave robotic system for natural ori_ce transluminal endoscopic surgery Ann. Acad. Med. Singap.. 2011;40:223{230.
[S116] Sutherland G. R., Maddahi Y., Gan L. S., Lama S., Zareinia K.. Robotics in the neurosurgical treatment of glioma Surg Neurol Int. 2015;6:1{8.
[S117] Suzuki N., Hattori A., Ieiri S., Tomikawa M., Kenmotsu H., Hashizume M.. Formulation of wire control mechanism for surgical robot to create virtual reality environment aimed at conducting surgery inside the body Stud Health Technol Inform. 2013;184:424{430.
[S118] Tan N., Margolis D. J., McClure T. D., et al. Radical prostatectomy: value of prostate MRI in surgical planning Abdom Imaging. 2012;37:664{674.
[S119] Tavakoli M., Aziminejad A., Patel R. V., Moallem M.. Multi-sensory force/deformation cues for sti_ness characterization in soft-tissue palpation Conf Proc IEEE Eng Med Biol Soc. 2006;1:837{840.
[S120] Tavakoli M., Aziminejad A., Patel R. V., Moallem M.. Tool/tissue interaction feedback modalities in robot-assisted lump localization Conf Proc IEEE Eng Med Biol Soc. 2006;1:3854{3857.
[S121] Tavakoli M., Patel R. V., Moallem M.. Haptic interaction in robot-assisted endoscopic surgery: a sensorized end-e_ector Int J Med Robot. 2005;1:53{63.
[S122] Tsai T. Y., Dimitriou D., Li J. S., Kwon Y. M.. Does haptic robot-assisted total hip arthroplasty better restore native acetabular and femoral anatomy? Int J Med Robot. 2016;12:288{295.
[S123] Meijden O. A., Schijven M. P.. The value of haptic feedback in conventional and robot-assisted minimal invasive surgery and virtual reality training: a current review Surg Endosc. 2009;23:1180{1190.
[S124] Vanmulken D. A., Spooren A. I., Bongers H. M., Seelen H. A.. Robot-assisted task-oriented upper extremity skill training in cervical spinal cord injury: a feasibility study Spinal Cord. 2015;53:547{551.
[S125] Veras E. J., De Laurentis K. J., Dubey R.. Design and implementation of visual-haptic assistive control system for virtual rehabilitation exercise and teleoperation manipulation Conf Proc IEEE Eng Med Biol Soc. 2008;2008:4290{4293.

[S126] Wang Z., Sun Z., Phee S. J.. Haptic feedback and control of a exible surgical endoscopic robot Comput Methods Programs Biomed. 2013;112:260{271.
[S127] Watanabe T., Abbasi A. Z., Conditt M. A., et al. In vivo kinematics of a robot-assisted uni- and multi-compartmental knee arthroplasty J Orthop Sci. 2014;19:552{557.
[S128] Wedmid A., Llukani E., Lee D. I.. Future perspectives in robotic surgery BJU Int.. 2011;108:1028{1036.
[S129] Wexner S. D., Bergamaschi R., Lacy A., et al. The current status of robotic pelvic surgery: results of a multinational interdisciplinary consensus conference Surg Endosc. 2009;23:438{443.
[S130] Wu F., Chen X., Lin Y., et al. A virtual training system for maxillofacial surgery using advanced haptic feedback and immersive workbench Int J Med Robot. 2014;10:78{87.
16
[S131] Xu Z., Song C., Wu W.. [Haptic tracking control for minimally invasive robotic surgery] Sheng Wu Yi Xue Gong Cheng Xue Za Zhi. 2012;29:407{410.
[S132] Yamamoto T., Abolhassani N., Jung S., Okamura A. M., Judkins T. N.. Augmented reality and haptic interfaces for robot-assisted surgery Int J Med Robot. 2012;8:45{56.
[S133] Ye D., Moza_ari-Naeini H., Busart C., Thakor N. V.. MEMSurgery: an integrated test-bed for vascular surgery Int J Med Robot. 2005;1:21{30.
[S134] Zareinia K., Maddahi Y., Ng C., Sepehri N., Sutherland G. R.. Performance evaluation of haptic hand-controllers in a robot-assisted surgical system Int J Med Robot. 2015;11:486{501.
[S135] Zhang D., Zhu Q., Xiong J., Wang L.. Dynamic virtual _xture on the Euclidean group for admittance-type manipulator in deforming environments Biomed Eng Online. 2014;13:51.
[S136] Zhang J., Wei W., Ding J., Roland J. T., Manolidis S., Simaan N.. Inroads toward robot-assisted cochlear implant surgery using steerable electrode arrays Otol. Neurotol.. 2010;31:1199{1206.
[S137] Zhao L. C., Meeks J. J., Nadler R. B.. Robotics in urologic surgery Minerva Urol Nefrol. 2009;61:331{339.
[S138] Zhou C., Xie L., Shen X., Luo M., Wu Z., Gu L.. Cardiovascular-interventional-surgery virtual training platform and its preliminary evaluation Int J Med Robot. 2014.
[S139] Zorn K. C.. Robotic radical prostatectomy: assurance of water-tight vesicourethral anastomotic closure with the Lapra-Ty clip J. Endourol.. 2008;22:863{865.
[S140] Barthel A., Trematerra D., Nasseri M. A., et al. Haptic interface for robot-assisted ophthalmic surgery Conf Proc IEEE Eng Med Biol Soc. 2015;2015:4906{4909.
[S141] Tezuka M., Kitamura N., Miki N.. Micro-needle electro-tactile display Conf Proc IEEE Eng Med Biol Soc. 2015;2015:5781-5784.

Table 1: Number of studies passing different stages of the review

Phase	Number of records
Phase 1: Initial search	141
Phase 2: Screening	141
Phase 3: Full text and ranking	125
Phase 4: Inclusion (Rank ≥ 3)	74

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Table 2: Distribution of ranked articles

Rank	**Number of records**
No rank: full text unavailable	16
Rank 1: least relevant	26
Rank 2: less relevant	25
Rank 3: relevant	34
Rank 4: more relevant	26
Rank 5: highly relevant	14
Total	141

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Table 3: All studies assessed by both raters

Haptics	Tactile	Score	Review	Patients	Studies
NO	NO	1	NO	NO	[S124, S77, S41, S95, S37, S104, S67, S129, S139, S46, S54, S59]
NO	NO	1	NO	YES	[S25, S27, S19, S118, S56, S2, S43, S13]
NO	NO	2	NO	NO	[S30, S31, S71, S79, S42, S44, S40, S107, S136, S72, S36, S55]
NO	NO	2	NO	YES	[S98]
NO	NO	3	NO	NO	[S11, S50, S51, S6]
NO	NO	3	YES	NO	[S83]
NO	NO	3	YES	YES	[S29]
NO	YES	4	NO	NO	[S94]
YES	NO	1	NO	NO	[S88, S58, S92, S66, S32]
YES	NO	1	NO	YES	[S127]
YES	NO	2	NO	NO	[S15, S130, S68, S14, S5, S125, S69, S101, S86, S74]
YES	NO	2	NO	YES	[S122, S78]
YES	NO	3	NO	NO	[S62, S138, S102, S73, S110, S47, S99, S45, S52, S132, S90, S89, S103, S81, S64, S17, S3, S133, S106, S33]
YES	NO	3	NO	YES	[S93]
YES	NO	3	YES	NO	[S113, S128, S61, S123, S80, S85]
YES	YES	3	YES	YES	[S4]
YES	NO	4	NO	NO	[S12, S87, S135, S75, S126, S57, S109, S16, S7, S9, S21, S97, S91, S22, S114, S1, S8, S112, S119, S120, S140, S141]
YES	NO	4	NO	YES	[S116]
YES	NO	4	YES	NO	[S63, S18]
YES	NO	5	NO	NO	[S24, S26, S34, S20, S35, S96, S115, S111, S60, S48, S38, S105, S121, S49]

Table 4. Studies tried on patients

Robot	Tried_ON	Description	Studies
NeuroArm robot	Patient	NeuroArm integrated in neurosurgical room and tried on 18 patients with glioma	[S116]
MAKO TGS	Patient	Demonstration of successful use of robot assisted unicompartmental knee arthroplasty	[S93]

Table 5. Studies with the score of 5 in relevance

Robot	Tried_ON	Description	Studies
Haptic pedal	Simulation	Phantom desktop is used alongside the Haptic pedal to assess cue via multiple channels	[S24]
Phantom Omni	Simulation	Phantom Omni is used alongside developed optical force sensor for MIS applications	[S26]
RCM robot		**Development** of a haptic remote centre of motion (RCM) mechanism	[S34]
Coaxial needle insertion		**Development** of a coaxial needle insertion robot	[S20]
RoboMaster1		**Design** of RoboMaster1	[S35]
Parasurg		**Development** of hybrid parallel robot for MIS	[S96]
Notes	Animals	**Developed** endoscopic platform tested with porcine stomach models and 5 live pigs	[S115]
MBARS		Adding haptic capabilities to MBARS robot used in knee joint arthroplasty	[S111]
		Sensor-Based Force Feedback in a Compact Laparoscopic Surgery Robot	[S60]
Pneumatic balloon tactile display	Simulation	Tested sensed accuracy through synthetic stimulations. Systems mountable on da Vinci system	[S48]
Microgripper		**Development** of shape memory alloy actuated microgripper	[S38]
		Development of haptic forceps	[S105]
Endoscopic end-effector		**Development** of an endoscopic end-effector	[S121]
Pneumatic balloon actuator		Perception tests with the pneumatic balloon actuator	[S49]

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Table 6. Studies with the score of 3 and 4

Robot	Tried_ON	Description	Studies
Phantom Omni	Cadaver/Simulation	Endoscopic probe - controlled by Phantom Omni	[S12]
da Vinci Surgical System	Simulation	SynTouch BioTac tactile sensor mounted on da Vinci system working on simulate heart tissue	[S87]
Phantom Omni	Simulation	Application of pseudo haptic and forcefeedback together for palpation	[S62]
NeuroArm robot	Patient	NeuroArm integrated in neurosurgical room and tried on 18 patients with glioma	[S116]
CIS Virtual Training Platform	Simulation	Platform **development** for education	[S138]
		A framework for virtual fixtures for tissue manipulation haptics	[S135]
Omega 7	Simulation	Omega 7 with an add-on wearable finger-tip device	[S75]
Omega 6		Omega 6 haptic device to control Anubis endoscope compared to conventional control	[S102]
Endoscopic robotic system		**Development** of an endoscopic robotic system with multi-dof manipulator	[S126]
Acrobot Sculptor	Simulation	Dry bone model cam resection	[S73]
Endoscopic snake robot	Simulation	Control and derivation of Snake robot and its assessment is simulation	[S57]
Needle steering		**Development** of a needle steering biopsy guide with MRI compatibility	[S109]
Mimic dV-Trainer	Simulation	Mimic dV-Trainer with HMD simulating augmenting an operation with a da Vinci system	[S110]
RIO Robotic Arm	Simulation	Performance of robotic system versus manual resection of tumour in modelled femurs	[S47]
Robocast		Optical sensors and robot assistance in keyhole neurosurgery tested on a model brain/skull	[S16]
Phantom Omni	Simulation	Two phantom Omni robots, one for each hand on master side for teleoperation	[S99]
		A framework to control multiple robotic systems in master-slave scenarios	[S7]
KAIST- Ewha colonoscopy	Simulation	Simulation platform developed at KAIST	[S45]
	Simulation	Haptic Controller modelling and simulation	[S52]
Air jet Haptic lump display		**Development** and characterisation	[S9]

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Phantom		Augmented reality and master slave operations using Phantoms	[S132]
Blazer II HTD	Simulation	Electrophysiological catheter	[S90]
Phantom Omni		VR based simulation system for laproscopic rectum surgery	[S89]
Robocast		**Development** of the Robocast system and its evaluation using Omega 3 device	[S21]
Phantom Omni	Simulation	Omni is used for centering based on Lumen position for simulated colonoscopy	[S103]
Paramis	Animals	Platform developed for MIS, tested with one porcine liver	[S97]
		Development of force reflecting robot for catheter navigation	[S91]
		Gaze Contingent Motor Channeling to improve cognitive load during operation	[S81]
Robocast		Introduction to Robocast project and path planner components	[S22]
Phantom Desktop	Simulation	Phantom desktop as Master, with a 1DOF developed device as slave to estimate environmental forces	[S114]
		Master-slave needle insertion using commercially avaiable Phantom and Puma robots	[S1]
		Algorithms for force estimation algorithms in Master-Slave systems	[S8]
MAKO TGS	Patient	Demonstration of successful use of robot assisted unicompartmental knee arthroplasty	[S93]
da Vinci Surgical system		Addition of a new Axial force free joint to the system, early stage prototype	[S112]
	Simulation	Algorithms for collision detection in haptics	[S64]
modiCAS system		**Development** of a cooperative interface and haptic constraints	[S17]
Force reflective interface		**Development** and evaluation of a force reflective master slave system for endoscopy	[S119]
Froce reflective interface	Simulation	Tool/tissue interaction in the force reflective system	[S120]
da Vinci Surgical System		Augmented reality for sensory substitution was added to conventional robot suturing on a tube	[S3]
MEMSurgery	Animals	**Development** of testbed for vascular surgery and evaluation with Wistar rats	[S133]
LANS		**Development** of the LANS tool actuator mounted on a NeuroMate robot	[S106]

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Opthalmic surgery assistant		**Development** tested in a master-slave configuration with a Phantom premium 1.5	[S140]
Laproscopic grasper	Animals	**Develeoped** a laproscopic grasper with measurement capability and tried on animal tissues	[S33]
Micro-needle electrode array	Simulation	New Tactile device that consists of an array of needle-type electrodes offering tactile feedback	[S141]

Table 7. Studies indicating tactile sensing addition

Robot	Tried_ON	Description	Studies
da Vinci Surgical System	Simulation	SynTouch BioTac tactile sensor mounted on da Vinci system working on simulate heart tissue	[S87]
Omega 7	Simulation	Omega 7 with an add-on wearable finger-tip device	[S75]
Mimic dV-Trainer	Simulation	Mimic dV-Trainer with HMD simulating augmenting an operation with a da Vinci system	[S110]
Tactile sensing Instrument	Animals	Tactile sensing Instrument (TSI) with 60-element pressure sensors detecting tumor in animal tissue	[S94]
Pneumatic balloon tactile display	Simulation	Tested sensed accuracy through synthetic stimulations. Systems mountable on da Vinci system	[S48]
Micro-needle electrode array	Simulation	New Tactile device that consists of an array of needle-type electrodes offering tactile feedback	[S141]

Table 8. Different robotic probe/interfaces used by studies

Robot	Studies
Acrobot Sculptor	[S73]
Air jet Haptic lump display	[S9]
Blazer II HTD	[S90]
CIS Virtual Training Platform	[S138]
Coaxial needle insertion	[S20]
da Vinci Surgical System	[S87, S112, S3, S50, S51, S6]
Endoscopic end-effector	[S121]
Endoscopic robotic system	[S126]
Endoscopic snake robot	[S57]
Force reflective interface	[S119]

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Froce reflective interface	[S120]
Haptic pedal	[S24]
KAIST- Ewha colonoscopy	[S45]
LANS	[S106]
Laproscopic grasper	[S33]
MAKO TGS	[S93]
MBARS	[S111]
MEMSurgery	[S133]
Micro-needle electrode array	[S141]
Microgripper	[S38]
Mimic dV-Trainer	[S110]
modiCAS system	[S17]
Needle steering	[S109]
NeuroArm robot	[S116]
Notes	[S115]
Omega 6	[S102]
Omega 7	[S75]
Opthalmic surgery assistant	[S140]
Paramis	[S97]
Parasurg	[S96]
Phantom/Omni/Desktop	[S12, S62, S26, S99, S89, S103][S114][S132]
Pneumatic balloon actuator	[S49]
Pneumatic balloon tactile display	[S48]
RCM robot	[S34]
RIO Robotic Arm	[S47]
Robocast	[S16, S21, S22]
RoboMaster1	[S35]
Tactile sensing Instrument	[S94]

Table 9. Different surgical specialties listed by the literature

Specialty	Studies
Anaesthesia	[S20]
Cardiology	[S138, S135, S90, S91, S6]
Gastroenterology	[S102, S126, S57, S45, S115, S103, S120, S121]
General Surgery	[S87, S62, S63, S75, S11, S24, S26, S34, S110, S29, S99, S7, S18, S113, S35, S52, S9, S96, S132, S128, S89, S97, S81, S94, S61, S1, S123, S60, S48, S112, S38, S49, S50, S51, S33, S141]

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Gynaecology	[S83]
Neurosurgery	[S12, S116, S16, S21, S22, S106]
Ophthalmology	[S140]
Orthopaedics	[S4, S73, S47, S111, S93, S17]
Radiology	[S109]
Surgical Education	[S114, S8, S64, S3, S105]
Urology	[S80]

Figure 1. Number of studies at different stages of development

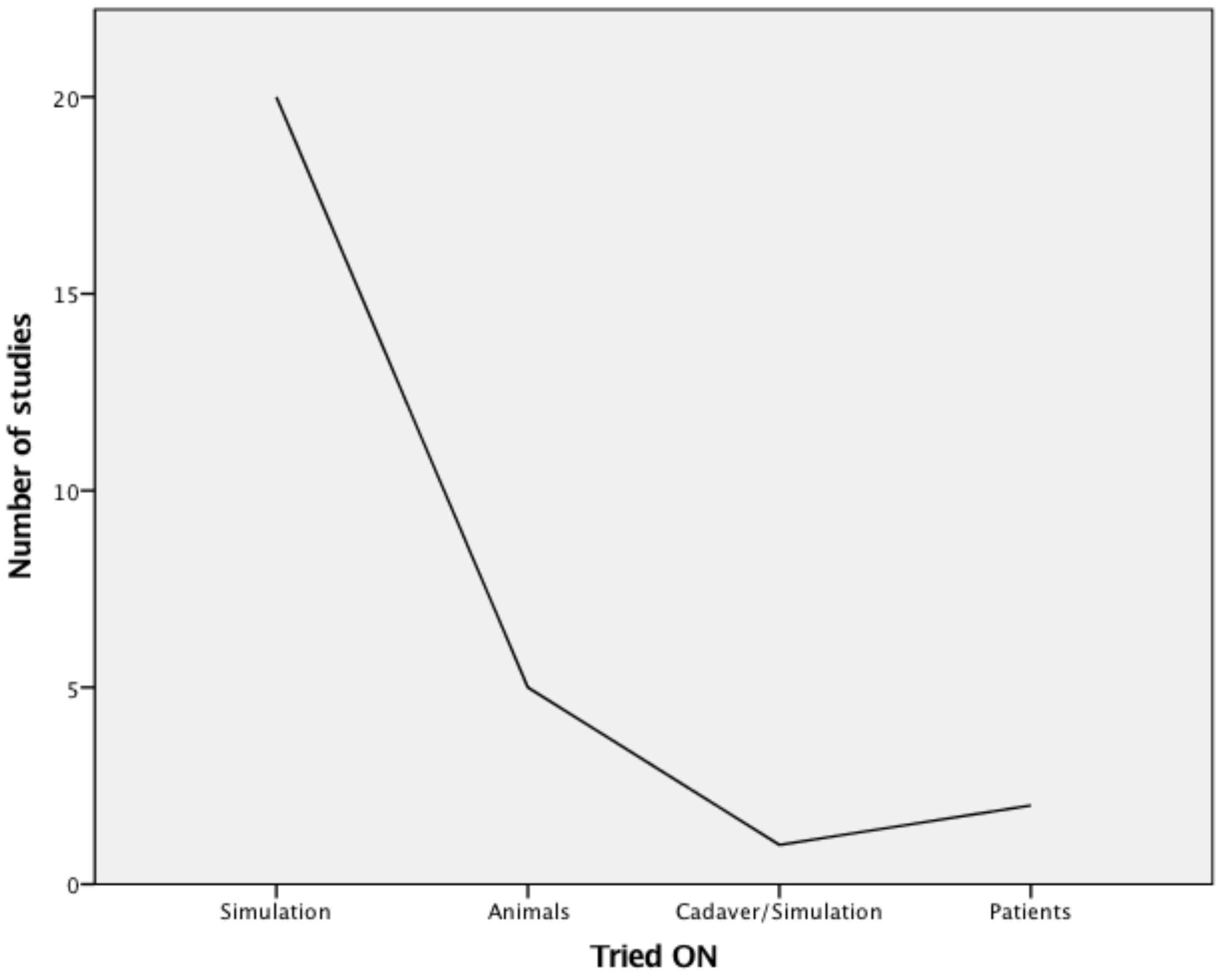

Figure 2. Robotics use in different clinical domains