Future perspectives in robotic surgery

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What’s known on the subject? and What does the study add?
Robotic surgery in its current form has established itself as a viable treatment option for several indications and the gold standard for a few indications. This has occurred because of the improved technology built into the robotics system. This paper looks at the brief history of robotics in surgery. Then we review in more detail some of the future possible additions to the technological armamentarium that might significantly improve the ways that surgeons perform robotic surgery.

KEYWORDS
robotic surgery, novel technology, haptics, augmented vision, laparoendoscopic single-site surgery, miniature robots, flexible robotics

• Robotics of the current day have advanced significantly from early computer-aided design/manufacturing systems to modern master-slave robotic systems that replicate the surgeon’s exact movements onto robotic instruments in the patient.
• Globally >300 000 robotic procedures were completed in 2010, including ~98 000 robot-assisted radical prostatectomies.
• Broadening applications of robotics for urological procedures are being investigated in both adult and paediatric urology.
• The use of the current robotic system continues to be further refined. Increasing experience has optimized port placement reducing arm collisions to allow for more expedient surgery. Improved three-dimensional camera magnification provides improved intraoperative identification of structures.
• Robotics has probably improved the learning curve of laparoscopic surgery while still maintaining its patient recovery advantages and outcomes.
• The future of robotic surgery will take this current platform forward by improving haptic (touch) feedback, improving vision beyond even the magnified eye, improving robot accessibility with a reduction of entry ports and miniaturizing the slave robot.
• Here, we focus on the possible advancements that may change the future landscape of robotic surgery.

ROBOTICS OF THE PRESENT DAY

The Czech playwright Karel Capek is credited with introducing the word ‘robot’ in his play Rossum’s Universal Robots in 1921 [1,2]. The word stems from the Slavic word robota meaning serf labour. Later popularized by science fiction writer Isaac Asimov in the 1940s [1], robotics finally became reality in 1961 with the first industrial robot, UNIMATE, at a General Motors factory assembly line in Trenton, NJ, USA [3]. Whereas industrial robots typically are used to operate in areas that are dangerous or not easily accessible by humans, medical surgical robots were first introduced in the 1980s to augment the medical staff by imparting superhuman capabilities: high motion accuracy and enabling interventions that would be otherwise physically impossible [4].

Early surgical robots were computer-aided design/manufacturing (CAD/CAM) systems [5]. These used pre-fixed anatomical landmarks as points of recognition and registration by the computer to allow movement within set confines. The rigid and predictable behaviour of bone was first exploited [1]. RoboDoc (Integrated Surgical systems, Sacramento, CA, USA), first used in humans in 1992, incorporated prior two-dimensional (2D) fluoroscopic imaging to improve placement and dimensional accuracy of prosthetic implants by robotic drilling and bone preparation [1,4–6]. NeuroMate was USA Food and Drug Administration (FDA) approved in 1997 (Integrated Surgical Systems) to assist in stereotactic functional brain surgery based upon preoperative head imaging [1,2].

Robotics was first introduced in urological surgery in the late 1990s for both prostate and renal access. ProBot (prototype from Imperial College, London, UK) was a robotic resection device with seven degrees of freedom designed for automated TURP for BPH [2,7,8]. Meanwhile, PAKY-RCM (Percutaneous Access to Kidney—Remote Centre of Motion) and AcuBot were both developed at Johns Hopkins University. These robots transformed 2D biplanar fluoroscopy images into its own 3D robotic space for precise percutaneous renal access [2,7,9,10]. Variations of the CAD/CAM robots have been used in many subspecialties of medicine, combining various imaging methods with the precision of robotics. A 3D ultrasound-guided robotic needle placement can now even account for cardiac and respiratory motion reducing invasiveness and user bias [11].

The modern age of surgical robots began with robotic systems using continuous input from surgeons to change their movements according to input in real time [2]. In 1993, Automated Endoscopic System for Optimal Positioning (AESOP; Computer Motion Inc., Goleta, CA, USA) was the first FDA-approved endoscopic manipulator [2]. AESOP
manoeuvres the endoscopic camera according to the surgeon’s commands transmitted by either foot pedals or voice alone. With advances in robotic engineering, the integrated master-slave systems were developed allowing very complex minimally invasive surgery to be performed. The ZEUS robotic system (Computer Motion Inc.) combined an AESOP unit with two robotic manipulator arms. A surgeon seated at a console used polarizing glasses to view a flat screen to gain a 3D image and manipulated handles to control the slave robot. Additional abilities of voice control integration and telemonitoring were provided [2,7]. FDA approval was granted in 2002. However, Computer Motion Inc. was merged with Intuitive Surgical Inc. (Sunnyvale, CA, USA) and the ZEUS system was discontinued.

The da Vinci® Surgical System (Intuitive Surgical Inc.) emerged as the state-of-the-art telesurgical system. This master-slave robotic system replicates the surgeon’s exact movements on the master controls onto robotic instruments in the patient using their EndoWrist® technology [2,7]. A binocular lens and camera system transmits magnified 3D images to the surgeon console. In 2000, it was cleared by the FDA for use in general laparoscopic surgery [6,12], followed by clearances in 2001 for radical prostatectomy (RP) and 2005 for urological surgical procedures [12]. The most recent edition, the da Vinci Si, was launched in April 2009 introducing improved high-definition imaging and further streamlining of the entire system. The system also allows the addition of a second surgeon console for surgical training or combined two surgeon procedures [12].

As of the end of 2010, 1752 da Vinci systems were installed in >1500 hospitals, in 44 countries around the world: 1285 in the USA, 316 in Europe, and 151 in the rest of the world [12,13]. Globally >300 000 robotic procedures were completed in 2010, including > 98 000 robot-assisted RPs (RARP) [12,13]. Pioneering work assessing the feasibility of robotic surgery with RARP has progressed in the last decade to RA radical cystectomy and RA renal procedures, including partial nephrectomy, pyeloplasty, and nephroureterectomy with excision of bladder cuff. Broadening applications of robotics for urological procedures are being investigated in both adult and paediatric urology with efforts published for RA pyelolithotomy and management of urolithiasis, robotic management of vesico-vaginal fistula, and RA ureteroneocystotomy and ureteric tapering [14].

The use of the current robotic system continues to be further refined. Increasing experience has optimized port placement reducing arm collisions to allow for more expedient surgery. Improved 3D camera magnification up to >×15 provides improved intraoperative identification of structures [14]. Robotics has probably improved the learning curve of laparoscopic surgery while still maintaining its patient recovery advantages and outcomes. The future of robotic surgery will take this current platform forward by improving haptic (touch) feedback, improving vision beyond even the magnified eye, improving robot accessibility with a reduction of entry ports and miniaturizing the slave robot. Here, we focus on the possible advancements that may change the future landscape of robotic surgery.

ADVANCES IN HAPTIC FEEDBACK

Robotic arms allow the surgeon to precisely manoeuvre surgical instruments with high-degree-of-freedom movements. One shortcoming frequently discussed is the lack of haptic feedback. Haptics describes touch feedback, which includes both kinaesthetic (forces and positions of muscles/joints) and cutaneous (tactile) feedback encompassing distributed pressure, temperature, vibration, and texture [15,16]. Surgical techniques rely on precisely handling tissue. Sensory feedback of haptic cues is considered an essential part of open surgery. Robotic surgeons have thus far compensated using the improved visual feedback cues to estimate forces, but fine manipulation may still be compromised with diminished haptic feedback.

Efforts to return haptic feedback to the surgeon require both artificial haptic sensors on the patient-side to acquire information and an interface to convey this information to the surgeon [15]. A fundamental limitation is the trade-off between system stability and transparency for force feedback, where small errors and delays in the system can cause uncontrollable oscillations and instability in the surgical display [15]. Furthermore, a dexterous robot has seven degrees of freedom of movement including translational, rotational and gripping movements. All degrees of freedom cannot be actuated on the master console signifying that the system cannot provide force feedback in certain directions. This effect may be negligible or detrimental depending on the directions of force feedback lost [15].

Kinaesthetic or force feedback systems are commercially available but in surgical practice are severely limited by the constraints on size, geometry, cost, biocompatibility, and sterilizability [7,15]. Researchers have created specialized grippers that can attach to the jaw of the existing instruments. Applied force by the surgeon is reduced with this force feedback, thereby reducing potential tissue damage [17]. The effectiveness of haptic feedback on surgeon performance in phantom patients has been tested by several researchers. These preclinical tests have shown force feedback to reduce forces without a significant increase in trial time [15,17]. The problem again becomes the cost-benefit ratio of these tools whether by modifying current instruments or re-engineering the instruments altogether.

One recent solution is VerroTouch™, a haptic sensation system under development by Kuchenbecker et al. [18] (Fig. 1) [19]. VerroTouch is a mechanically customized add-on system that attaches onto the da Vinci S robotic system arms beneath the sterile drapes. By moving the haptic sensors from the instruments to the robotic arms, the sensors do not make patient contact and therefore do not require sterilization or reprocessing. VerroTouch analyses high-frequency accelerations in the robotic arm movements and processes these accelerations in real time. Vibrotactile feedback is then provided as a combination of both naturalistic high-frequency vibrations at the surgeon’s hand controls and/or stereo sound [18].

Surgeon trials have shown that surgeon responses to audio and direct haptic feedback on the master controls are generally positive. Negative responses reflect the importance of filtering real haptic sensation from background friction within the robotic system itself [19]. Early in vitro
High-definition robotic vision continues to improve with finer resolution via shrinking electronic components. Further advances are underway to enhance surgical vision beyond even the magnified eye of the surgical robot. This can be achieved via two approaches: (i) combining the surgical field with adjunct real-time imaging or (ii) improving visual resolution beyond the surface anatomy to visualize anatomical structures (vessels, nerves) or small tumours difficult to see with the naked eye.

Augmented vision is the concept of integrating computer-generated images from preoperative studies overlaid onto the live video image during surgery [21]. This image-guided surgery is typically based on bony landmarks and hence possible in neurosurgery, maxillofacial surgery, and orthopaedics. Efforts to extrapolate its use to abdominal surgery becomes challenging due to the deformable viscera and constant shifting from breathing and movement of surgical instrumentation [7,21].

Progress in this field has been reported recently in minimally invasive renal surgery [21]. New tracking systems are being developed to achieve dynamic real-time overlay onto a surgical field by accounting for the dynamic movement of the target organ. A 3D positional correlation between the overlaid images and the surgical instruments becomes feasible without the limitations of using only real-time data acquisition. This allows CT or MRI image overlay depending on the goals of surgery. This surgical navigation has been demonstrated during both laparoscopic partial nephrectomy and laparoscopic nerve-sparing RP [21]. Ukimura and Gill [21] are further developing this navigation software to improve the precision and function of the augmented reality visualization system. A body-‘global positioning system’ has been introduced as a new organ-tracking system. This may soon allow for predictive navigation systems where ‘surgical radar’ will predict the ideal surgical plane before performing the actual surgical manoeuvre. A colour-coded zonal navigation model would then be overlaid on the surgical field to help achieve better oncological and functional outcomes (Fig. 2) [21].

Other methods have been explored for real-time image and anatomical localization data acquisition. Intraoperative nerve stimulation and tumescence monitoring with CaverMap (Blue Torch Corporation, Boston, MA, USA) [22] has been used to demarcate cavernous nerves during RARP. Power-Doppler TRUS (B-K Medical, Copenhagen, Denmark) has been used to identify and confirm pulsatile blood flow within the neurovascular bundles whose preservation correlates with superior erectile function recovery [23]. Likewise, intraoperative ultrasound is widely used to identify and demarcate resection edges during RA partial nephrectomy. Multiple-input display is supported by the da Vinci surgeon console using the TilePro® system to allow ‘picture in picture’ viewing. Drawbacks include the necessity of additional surgical personnel to manipulate the imaging device and the potential requirement of an additional assistant port.

During RARP, intraoperative TRUS navigation allows for: (i) identification of hypoechogenic prostatic nodules, (ii) precision during lateral pedicle transaction and neurovascular bundle release, (iii) calibrated wider dissection at the site of suspected extracapsular extension, (iv) tailored dissection of the individual prostate apex and (v) facilitation of the posterior bladder neck transection (Fig. 3) [24]. Used in this setting, TRUS during laparoscopic RP allowed intraoperative prediction of pT2 vs pT3 disease with 85% accuracy and a statistically significant decrease in positive margins in pT3 disease by following real-time recommendations of calibrated wider site-specific dissection [25].

Manual TRUS manipulation discards potentially important positional data. Han et al. [26] have developed a robotic TRUS probe manipulator (TRUS robot) and 3D-reconstruction software to be used concurrently with the da Vinci surgical robot in a tandem–RA laparoscopic RP. This TRUS robot allows the surgeon to manipulate the TRUS guidance without additional personnel required to manipulate the TRUS in the limited space bound by the patient’s legs, operative table and the da Vinci surgical robot (Fig. 4) [26]. The additional positional information also allows for precise volume measurement, 3D reconstruction, and navigation display [26].

FIG. 1. VeroTouch system components integrated with the Intuitive Surgical da Vinci S Surgical System. Vibration sensors on the robotic arms are analysed and then reproduced on the vibration actuators on the surgeon console. (Permission Requested From McMahan W. Tool Contact Acceleration Feedback for Telerobotic Surgery, IEEE Transactions on Haptics [19].)
Novel technologies are being developed that move us beyond traditional imaging into the realm of microscopic surgical vision. Multifocal photon microscopy (MPM) [27] allows real-time intraoperative histopathology without needing excision or administration of contrast agents (Fig. 5). MPM enables the imaging of fresh, living, unprocessed tissue utilizing intrinsic tissue emissions by using excitation of two low-energy photons to cause non-linear excitation. Tissue autofluorescence from intracellular molecules and second harmonic generation from non-centrosymmetric tissues generates distinctive optical signals allowing imaging at sub-micron resolution. Using each tissue’s unique signatures, MPM can identify all relevant prostatic and periprostatic structures including nerves, blood vessels, capsule, underlying acini and also pathological changes such as prostate cancer. Ex vivo testing has shown MPM to be comparable to the ‘gold standard’ haematoxylin and eosin-stained histopathology of the same specimen [27]. This allows detailed feedback beyond pre-surgical imaging and predictors without requiring the tissue destruction and time-delay of intraoperative frozen sections. An early custom-made MPM system has proven safe and effective in imaging of the prostate and periprostatic tissue. However, the system requires further miniaturization and integration with the robotic surgical platform for further study in a true surgical setting [27].

In February 2011, Intuitive Surgical Inc. received FDA clearance for a da Vinci fluorescence imaging system allowing surgeons to image vasculature in 3D beneath tissue surfaces in real time [12]. Phase I studies are underway to evaluate its use with the i.v. administration of indocyanine green to optimize near infrared imaging of cortical renal tumours [28]. Ultimately, the future success of any advanced imaging systems lies with its ability to simply enhance surgical vision without becoming overly cumbersome.

ADVANCES IN ACCESSIBILITY

Among the current drawbacks to robotic surgery, accessibility to the patient remains a concern with the present da Vinci platform requiring a large sterile field. Complex laparoscopic procedures demand multiple trocar access for the endoscopic camera, two or three robotic instrument ports, as well as any additional assistant ports. Efforts have been made on numerous fronts to miniaturize and further mobilize the robotic platform as well as to re-engineer a robotic platform using current advances in laparoendoscopic single-site surgery (LESS) and natural orifice transluminal endoscopic surgery (NOTES).

MINIMIZING TROCAR ACCESS

The underlying difficulty of LESS results from the need to overcome the poor ergonomics of the endoscope and instrument collisions through a single-port entry while still maximizing efficiency and precision. NOTES uses natural orifices to extract surgical specimens, which may initially sound appealing. However, these approaches whether transgastric, transvaginal, transvesical or transcolonic add the potential risk of viscerotomy to the procedure [29].

In 2005, Hiriano et al. [30] were the first to report urological single-incision surgery by their use of a resectoscope tube and standard laparoscopic instruments to perform a retroperitoneoscopic adrenalectomy. In 2007, two groups independently reported the first LESS transumbilical nephrectomy [29,31]. Multiple access devices have since been FDA approved for LESS. Many clinical series have reported the use of LESS across the spectrum of urological procedures [29]. To decrease instrument clashing and increase manoeuvrability, instruments have been designed to improve intraoperative ergonomics by using a combination of pre-bent curved, flexible, and articulating designs with high-definition, low-profile flexible endoscopes [29]. With its superior ergonomics, optical magnification and surgical dexterity, robotic surgical platforms are an ideal addition in the future of LESS/NOTES [32]. In 2008, Box et al. [33] reported the first hybrid RA
NOTES in a porcine model using combined transvaginal and transcolonic access with a single midline abdominal trocar. Further work in the porcine model, using a combination of umbilical and transvaginal access, showed the feasibility and enhanced suturing of RA NOTES on renal surgery [34]. In 2009, Kaouk et al. [35] reported the first successful RA single-port procedures in humans including RP, dismembered pyeloplasty, and radical nephrectomy via a multichannel umbilical port. The use of a GelPort (Applied Medical, Rancho Santa Margarita, CA, USA) as the access platform has improved adequate spacing and flexibility of port placement for both robotic and assistant access [36].

Despite the potential advantages, technical difficulties that still must be overcome include robotic arm collisions, limited triangulation despite EndoWrist capability and counterintuitive camera angles [29,33,35]. New techniques such as ‘chopstick surgery’ [37] are being tested to help overcome such limitations using the currently available robotic platforms (Fig. 6). The chopstick arrangement crosses the instruments just inside the abdominal wall so that the right instrument is on the left side of the target, and the left instrument on the right. This counterintuitivity of handedness is then corrected using the robotic console to drive the ‘left’ instrument with the right-hand effector and vice versa. A pilot study by Joseph et al. [37] showed the feasibility of this arrangement using two wristed instruments of a da Vinci S robot while eliminating instrument collision and decreasing camera and clutch manipulations.

RA-LESS surgery may soon be a reality via VeSPA surgical instruments (Intuitive Surgical Inc.) specifically designed to work with the da Vinci Si surgical system (Fig. 7) [38]. The initial laboratory experience in urology has been reported in the porcine model showing technical feasibility and efficiency with pyeloplasties, partial and radical nephrectomies [38]. Limitations such as significant gas leakage and lack of articulation at the tip of the VeSPA instruments compared with the Endowrist instruments resulted in more challenging intracorporeal suturing [38]. In February 2011, a da Vinci Single-Site™ instrument kit using VeSPA instruments received its CE mark for clearance in the European market.
FDA clearance is still underway for the USA [12].

MINIATURIZATION OF THE ROBOTIC PLATFORM

Further efforts to advance LESS have also provided engineering headway into miniaturizing and mobilizing the robotic platform itself. The introduction of a next generation of smaller robotic prototypes is underway to miniaturize the robotic platform. The Laprotek system (EndoVia Medical, Norwood, MA, USA) is comprised of slave instrument ‘motor packs’ that are mechanically mounted on the existing bed rails of the operating table [7]. Using curved guide tubes to position its instruments intracorporeally, the Laprotek design occupies significantly less space and reduces arm collisions. Dachs and Peine [39] have proposed another design wherein robotic instruments have two moveable joints within the body permitting six degrees of freedom without requiring corresponding external pivoting motions (Fig. 8). This limits instrument movement outside the patient to a line, rather than the da Vinci system’s 3D cone-shaped motion envelope. Slave instrument motor packs could then be mounted on a streamlined mechanical arm further minimizing extracorporeal machinery size and reducing instrument collisions [7].

One final prototype named RAVEN, developed at the University of Washington, is mounted on the patient directly and can be both deployed remotely and teleoperated [6].

With this next generation of robots, initial interests in telerobotics may be rekindled, separating surgeon and the patient in space altogether. In the 1970s, telerobotics via remotely controlled surgical robots was the initial goal of robotics for both military and astronautic uses. Shortcomings of computer technology of the day made telepresence impractical at the time [1]. ‘Operation Lindbergh’ where a surgeon in New York, NY, USA performed a laparoscopic cholecystectomy in Strasbourg, France was a technical success using a ZEUS robotic system in 2001 [5]. However, concerns with the time delay of computer transmission, computer stability and patient safety funnelled engineering advances into other efforts.

With the miniaturization and separation of surgeon and robot via remote control, the next generation of robots may now allow telerobotics not only at great distances, but deep into the human body itself. A magnetic anchoring and guidance system (MAGS) is a moveable magnet- or needle-lockable platform that is introduced via a single access port. These deployable camera and instruments are positioned intra-abdominally on the abdominal wall. A magnetic anchoring and guidance system (MAGS) is a moveable magnet- or needle-lockable platform that is introduced via a single access port. These deployable camera and instruments are positioned intra-abdominally on the abdominal wall, creating trocar-free laparoscopy [29,40]. Feasibility trials with prototype MAGS have been shown in human trials for laparoscopic nephrectomy and appendectomy [41].

In contrast to MAGS that are stabilized intraperitoneally on the abdominal wall,
microrobots have been developed to mobilize within the peritoneal cavity itself. Oleynikov [6], Rentschler et al. [42,43] and Tiwari et al. [44] at the University of Nebraska have made multiple in vivo microrobots with significant early success (Fig. 9) [45]. Once inserted, these microrobots provide a remotely controlled platform for vision and surgical tasks. Mounted on two helical wheels and driven by direct current motors, these microrobots have shown sufficient traction to drive over slick, deformable viscera without causing injury [42]. A fixed-base pan-and-tilt camera microrobot, comprised upon tripod legs, has been designed to provide the surgeon vision of the microrobots and surgical field with 360° pan and 45° tilt view [43,46]. Light-emitting diodes provide illumination [46]. Semi-autonomous miniature robots have also been developed for simple surgical tasks in the event that the communication link between surgeon and patient has low bandwidth or very high latency [47]. Although early feasibility studies were demonstrated in a canine model [48], technical problems included the tethered design for the robot’s continuous power and lack of a self-cleaning mechanism for the camera lens [7,48]. Further engineering developments are underway for modular wireless wheeled robots with grasper, stapler and clamp, cautery, video camera, and physiological sensor payloads [49,45]. Another significant advance under investigation is intracorporeal microrobot locomotion [50]. The future in microrobots is promising; the insertion of multiple tools and cameras acting as a cooperative family is a not-so-distant possibility.

One final perspective in robotic engineering is flexible robotics possible due to miniaturization and refinement in fiberoptic and endoscopic technology. Flexible robotics potentiates endoscopy, further blurring the divide between endoluminal surgery (colonoscopy, cystoscopy) and standard extraluminal surgery (nephrectomy, cholecystectomy) [51]. A flexible endoscopy platform is also necessary in the further development of NOTES to safely obtain access to the peritoneal cavity and then repair the visceral incision upon withdrawal [44]. A robotic platform allowing precise, complex, and reproducible manoeuvres of flexible endoscopes inside hollow organs and 3D anatomical spaces should facilitate endoscopy and transfer the advantages of a rigid robotic system into the endoscopic environment [52].

The ViaCath system (EndoVia Medical) is a first-generation, teleoperated endoluminal device, consisting of a surgeon console and two flexible instruments located alongside a standard endoscope (Fig. 10) [53]. Each instrument, together with the positioning arm, provides seven degrees of freedom of movement. Early trials in porcine models exposed technical difficulties in intubating and positioning the instruments at the desired site and limited lateral force production by the instruments [6,7]. Second-generation endoluminal robotic systems are being further developed with a mechanical coupler to the position arm, a flexible shaft, and an articulating tip with an end-effector delivering full motion within the scope’s visual field [7,53]. The Sensei™ robotic catheter (Hansen Medical System, Mountain View, CA, USA) is another master-slave control system where the surgeon at the console remotely manipulates the catheter tip via movements intuitively mimicking the surgeon’s hand. Feasibility studies for the Sensei robotic catheter have been reported in uroterorenoscopy [51,52]. It is likely that a combination of such robotic systems, including flexible robots and deployable intracorporeal miniatures, will provide the future of robotic LESS and NOTES [51].

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CONFLICT OF INTEREST

None declared.

REFERENCES

3 Hutchinson A. The Top 50 Inventions of the Past 50 Years. Popular Mechanics December 2005
13 Intuitive Surgical®, Inc., intuitivesurgical.com. Investor Presentation Q42010
21 Ukimura O, Gills IS. Image-fusion, augmented reality and predictive
WEDMID ET AL.

22 Klotz L, Herschorn S. Early experience with intraoperative cavernous nerve stimulation with penile tumescence monitoring to improve nerve sparing during radical prostatectomy. Urology 1998; 52: 537–42
31 Tracy CR, Raman JD, Cadeddu JA, Rane A. Laparoendoscopic Single-Site Surgery in Urology: where have we been and where are we heading? Nat Clin Pract Urol 2008; 5: 561–8
34 Haber GP, Crouzet S, Kamoi K et al. Robotic NOTES (Natural orifice transluminal endoscopic surgery) in reconstructive urology: initial laboratory experience. Urology 2008; 71: 996–1000
39 Dachs GW, Peine WJ. A Novel Surgical Robot Design: Minimizing the Operating Envelope Within the Sterile Field. Proceedings of the 28th IEEE. 2006; New York City, USA: 1505–8

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Abbreviations: CA(D)(M), computer-aided (design) (manufacturing); FDA, USA Food and Drug Administration; (2)3D, (two) (three)-dimensional; AESOP, Automated Endoscopic System for Optimal Positioning; RP, radical prostatectomy; RA, robot-assisted; MPM, Multifocal photon microscopy; LESS, laparoendoscopic single-site surgery; NOTES, natural orifice transluminal endoscopic surgery; MAGS, magnetic anchoring and guidance system.