Accuracy of Touch-Based Registration During Robotic, Image-Guided Partial Nephrectomy Before and After Tumor Resection in Validated Phantoms

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Abstract word count: 300/300

Manuscript Word count: 2451/2500

Figures: 5

Abstract

Aim:

Image guided surgery (IGS) allows for accurate, real-time identification of critical structures during surgery. No prior IGS systems, however, have described a feasible method of intraoperative re-registration after manipulation of the kidney during robotic partial nephrectomy. We present a method for seamless re-registration during IGS and evaluate accuracy before and after tumor resection in two validated kidney phantoms.

Materials and Methods:

We performed robotic partial nephrectomy on two validated kidney phantoms- one with an endophytic tumor and one with an exophytic tumor- with our IGS system utilizing the da Vinci Xi robot. Intraoperatively, the kidney phantoms' surfaces were digitized with the robot instrument via a touch-based method and registered to a 3D segmented model created from cross-sectional images of the phantoms. Fiducial points were marked with a surgical marking pen and identified after the initial registration using a da Vinci robotic manipulator. Virtual images were displayed in TilePro as tumor resection was performed. After resection, re-registration was performed by re-identifying the fiducial points. The accuracy of the initial registration and re-registration was compared.

Results:

The root mean square (RMS) average of target registration error (TRE) was 2.53mm for the endophytic phantom and 4.88mm for the exophytic phantom. IGS enabled resection along preplanned contours. Specifically, the RMS average of the normal TRE over the entire resection surface was 0.75mm for the endophytic case and 2.15mm for the exophytic case. Both tumors were resected with grossly negative margins. Point-based re-

registration allowed for instantaneous re-registration with minimal impact on RMS TRE compared to the initial registration (from 1.34mm to 1.70mm pre-resection and 1.60mm to 2.10mm post-resection).

Conclusions:

We present a novel and accurate registration and re-registration framework for use during IGS for partial nephrectomy with the da Vinci Xi surgical system. The technology is easily integrated into the surgical workflow and does not require additional hardware.

Introduction:

Image guided surgery (IGS) during robotic partial nephrectomy facilitates accurate, real time identification of surgical anatomy and subsurface features of the kidney by registering preoperative cross-sectional imaging to intraoperative patient anatomy. There have been many efforts to develop IGS systems with goals of improving operative and warm ischemia times, as well as preserving renal parenchyma during tumor resection [1-3]. To do this, accurate registration is essential. Prior registration methods lack precision or require invasive fiducial placement and additional hardware which interfere with surgical workflow. We have previously described a robotic, touch-based registration method using the da Vinci robotic system. By intraoperatively tracing the tip of a robotic instrument over surface anatomy, a 3-dimensional surface point set can be generated and registered to a preoperatively segmented patient image [4-6]. Both the segmented patient anatomy and robotic instruments can be displayed virtually in TilePro™ and synchronously move with manipulation of the robotic instruments and endoscope.

Though we have shown the accuracy of this method in identifying critical structures during partial nephrectomy, registration accuracy can be affected over time by changes in patient anatomy during dissection, kidney mobilization, and tumor resection. Therefore, it is necessary to periodically re-register during IGS for partial nephrectomy to ensure precise, real-time identification of patient anatomy. However, there have been no studies evaluating re-registration accuracy for IGS after manipulation of the kidney for robotic partial nephrectomy on validated phantoms. One novel method of doing so would be to identify fiducials in the operative field, based on the initial, robotic touch-based registration. These fiducials could be periodically re-identified with the robotic instruments during partial nephrectomy, allowing for a fast and simple method of re-registration.

To the best of our knowledge, we have created the first system that utilizes a point-based, re-registration method to provide updated patient anatomy for IGS during partial nephrectomy with the da Vinci Xi robotic surgical system. We sought to evaluate the accuracy of this method after kidney tumor resection on validated phantoms.

Methods:

System Overview

We have developed a method of IGS relying solely on data obtained from the clinical da Vinci robotic system to enable a touch-based registration method [7]. Using the da Vinci application programming interface to obtain real-time kinematic data, our system computes the pose of each link of the da Vinci's manipulators [8]. This allows us to generate a set of surface data by lightly tracing the anterior surface of the patient's kidney using a da Vinci manipulator (shown as red dots in Fig. 1). We have previously published that approximately 28% of the surface needs to be traced for accurate registration of the entire kidney [9]. This data set enables registration between 3D images of patient anatomy (segmented from preoperative axial imaging) to the physical anatomy using a standard image registration algorithm [10]. Graphical models of the manipulators are automatically rendered and displayed synchronously with motion of the robot manipulators using a custom software module built with 3D Slicer (3dslicer.org), an open-source medical image computing and visualization platform [11]. Visualization is displayed directly in the da Vinci surgeon console through the console's TilePro interface (Fig. 1b,c).

Our system enables a means of point-based re-registration after kidney manipulation during partial nephrectomy. Motion of the kidney surface relative to its location at the time of initial registration leads to misalignment between the physical system and the image guidance visualization. Point-based re-registration helps correct such misalignment by enabling the image registration to be periodically updated by identifying surface fiducial points throughout the case (shown as purple dots in Fig. 1). Immediately after initial registration, these fiducial points are identified on the physical kidney surface by lightly touching them with a robotic manipulator (shown as yellow dots in Fig. 1c). The locations of these points are therefore known relative to the initial image registration and can be re-identified throughout the case to maintain alignment between the physical system and the image guidance visualization. This method of re-registration is almost instantaneous and less computationally intensive than the initial touch-based registration.

Experimental

We investigated the accuracy of point-based re-registration during simulated robotic partial nephrectomy procedures on two validated, patient-specific, hydrogel kidney phantoms: (1) a left kidney with an approximately 4 cm, exophytic tumor, and (2) a right kidney with an approximately 2 cm, predominantly endophytic tumor. Both phantoms were created from 3D printed casts of segmented cross-sectional patient images. The casts were injected with poly-vinyl alcohol (PVA) hydrogel and assembled to create accurate hilar, renal parenchymal and tumor anatomy. Prior experiments have validated the mechanical properties of these phantoms compared to living tissue [12].

For each experiment, the phantom was adhered to a rigid platform containing 6 spherical, “ground truth” fiducial markers (Fig. 2). Prior to experiments, the phantom platform was CT scanned with a section thickness of 0.3mm using an xCAT ENT Scanner (Xoran Technologies LLC, Ann Arbor, MI, USA). The kidney, tumor, hilar structures, and ground truth fiducials were manually segmented from the CT images. The segmentations produced 3D models of the kidney and tumor that were used for image guidance during experimentation. Segmentation of the fiducial markers enabled computation of the ground truth position of the kidney and tumor relative to the markers for comparison with registrations. Additionally, prior to surgery, surgeons drew a planned resection surface in each of the 3D kidney models. During surgery, the image guidance display included the planned resection contour as well as a 3mm tumor margin (Fig.3).

Experiments were performed with a clinical da Vinci Xi system. The robot was draped and docked over the surgical bed in a position approximating a standard peritoneal surgical approach. In order to determine the ground truth position of the kidney phantom relative to the robot, the surgeon first localized each of the ground truth fiducial markers on the phantom platform using a tracked Large Needle Driver (LND) instrument. Information from the ground truth fiducials served only to enable *post hoc* analysis of the accuracy of our touch-based registration and point-based re-registration; this information was not used intraoperatively by the image guidance system. Next, the surgeon lightly traced the anterior surface of the kidney using the LND instrument to acquire data for touch-based registration. After computing the initial touch-based registration, 15 ink dot fiducials were manually marked on the anterior surface with a surgical marker; each ink dot was then immediately localized using the LND instrument for use in re-registration. After identifying the ink fiducials, the phantom platform was moved to simulate manipulation of the kidney. Point-based re-registration was then performed by once again localizing the ink fiducials. Ground truth fiducials were also localized again for *post hoc* analysis of re-registration accuracy. Following re-registration, the surgeon resected the tumor using the image guidance display, as shown in Fig. 3. After completing tumor resection, the ink fiducials and ground truth fiducials were localized a final time using an LND instrument. The dissected phantom and platform were CT scanned immediately postoperatively to facilitate analysis of re-registration accuracy after resection.

Results:

Accuracy of initial touch-based registration was evaluated by comparing vertex positions of the registered 3D kidney model to the corresponding vertex positions in the ground truth 3D model. The target registration error (TRE) at each vertex was computed as the distance between that vertex and the corresponding vertex of the ground truth model. Heat maps were generated to identify the TRE of the initial registration based on the surface tracing for each phantom (Fig. 4a,c). The root mean square (RMS) average TRE over the entire kidney surface was 2.53mm in the endophytic case and 4.88mm in the exophytic case.

When evaluating registration accuracy in the context of the resection surfaces, only the component of TRE normal to the surface needs to be considered. The component of registration error parallel to the surface does not affect the accuracy of cutting along the surface with an instrument. The RMS average of the normal TRE over the entire resection surface was 0.75mm in the endophytic case and 2.15mm in the exophytic case (Fig. 4b,d).

The point-based re-registered image was compared to its initial registration, rather than the ground truth reference, to evaluate the isolated TRE of re-registration. The accuracy of point-based registration also depended on the number and distribution of fiducial markers used to calculate the registration. This dependence was investigated in *post hoc* analysis by computing numerous "leave-N-out" point-based registrations using subsets of the fiducial markers localized during experimentation. The Mean TRE for all possible combinations using the specified number of fiducials was calculated. The impact on the RMS TRE of point-based re-registration was minimal compared to our initial registration and almost instantaneous (increasing from 1.34mm to 1.70mm pre-resection and from 1.60mm to 2.10mm post-resection, depending on the number of points used in re-registration). The RMS TRE improved with an increase in number of fiducials identified and reached nadir at approximately 8 fiducials. The change was similar for both the endophytic and exophytic tumors in the phantoms (Fig. 5).

<u>Discussion</u>:

We have developed a novel IGS system for partial nephrectomy utilizing the da Vinci Xi robotic surgical system and evaluated point-based re-registration on validated kidney phantoms after tumor resection. By registering preoperative axial imaging, such as CT scan images, to intraoperative patient space, IGS allows for identification of hilar anatomy as well as subsurface kidney features related to the tumor. The technology has the potential to improve operative time and make margin selection easier for surgeons, optimizing the preservation of renal parenchyma. The ability to re-register during IGS is essential as dissection and manipulation inevitably leads to a change in the orientation and configuration of a target organ. Point-based re-registration by identifying fiducials marked with a sterile surgical marker allows for a quick and simple way to re-register and maintain accuracy during surgery. Furthermore, our system provides for both digitized anatomical surfaces and robotic manipulators in the TilePro™, complementing surgical workflow.

Our method of touch-based registration for IGS complements surgical workflow and only requires a software update for successful implementation. The idea of a touch-based registration with the da Vinci system was first suggested by Ong et al [4]. We previously demonstrated that the da Vinci manipulators can be localized with sufficient accuracy for image guidance [7]. By tracking the positions of the robot as the surgeon moves a manipulator across the surface of the patient anatomy, the IGS system creates a set of 3D surface data. This data set can be aligned with the surface of a preoperative, segmented kidney, allowing for accurate registration. Our prior analysis has shown this technique to be capable of achieving an average TRE of 3.69mm in a set of 700 registration experiments when using the da Vinci Si robotic system [7]. In our current study, we have translated our techniques to the da Vinci Xi robotic system and have generated similar TRE results.

Multiple other methods of registration for IGS have been previously evaluated. Teber et al first evaluated a method for IGS for laparoscopic partial nephrectomy by inserting fiducial markers on barbed needles directly into the kidney [2]. Intraoperatively, the fiducials were imaged with a mobile C-arm and segmented, allowing point-to-point registration between the imaged fiducials and those seen endoscopically. Though accurate with an error margin of 5mm, the technique requires invasive placement of fiducials as well as intraoperative imaging and segmentation, which interrupt surgical workflow and add to operative time.

A less invasive registration technique, such as manual registration, involves the surgeon visually aligning 3D images removed from the surgical field in the endoscopic view. Though manual registration might benefit the surgeon by having the preoperative imaging information displayed during surgery, the technique is often inaccurate as it depends on human hand-eye coordination and spatial reasoning to perform the registration. Multiple trials have shown variation in precision for manual registration [13-15].

Other groups have tried to employ stereo-endoscopes for instrument tracking and organ registration by triangulating surface points using a 3D stereoscopic endoscope and matching those to patient anatomy identified on preoperative imaging. For example, Su et al developed a multi-step CT-to-endoscope registration method by aligning a segmented kidney surface with stereoscopic video [1]. Similarly, Pratt et al utilized a combination of manual and endoscopic registration to align translation of the endoscope during partial nephrectomy [16]. Though endoscopic registration might eventually allow for a seamless way of integrating preoperative patient anatomy with the endoscopic display, the approach requires persistent direct line of sight between the camera and patient anatomy, which is often changed intraoperatively or obscured by smoke and blood. Furthermore, the method reduces the accuracy of tracking the robotic manipulators, as their positions in space are known only relative to the endoscopic image.

Though some of these methods have evaluated a means of updating IGS during surgery, no one has implemented a point-based re-registration method that can be instantaneously performed during robotic partial nephrectomy without interruption of the procedure[17]. It is necessary to maintain an up-to-date registration due to frequent changes in kidney orientation and configuration during mobilization, manipulation, and incision. In a study evaluating tissue deformation, Altamar et al found a 4.4mm average change in position of surface fiducials after making a transverse incision in porcine kidneys [18]. Furthermore, changes in renal perfusion during hilar clamping also can lead to anatomic and tissue deformation. Previous perfusion modeling demonstrated an average non-rigid kidney shift of 3mm from lack of vascular perfusion [19]. Thus, to minimize warm ischemia time and maintain accuracy during IGS, it is essential to have a flexible and fast method for re-registration. Our point-based technique provides for seamless re-registration that can quickly maintain accuracy during manipulation and incision of the kidney in a validated phantom.

Despite implementing a novel, point-based re-registration method for robotic partial nephrectomy, there are some limitations to our study. The technology has only been evaluated by a small number of surgeons and requires further evaluation for wide-spread, real-world application. Furthermore, though the phantoms used in our experiment have previously been validated for partial nephrectomy, they still may not accurately replicate living, human kidney tissue [12]. Additionally, intraoperative ultrasound, which is commonly used to enhance resection and tumor identification intraoperatively, was not evaluated in our experiment. It is possible that the incorporation of ultrasound may further improve accuracy during IGS and necessitate additional studies. We are planning prospective studies to evaluate our IGS system and our point-based re-registration method in vivo.

Conclusions:

We have developed the first system that uses a point-based, re-registration method to update patient anatomy during IGS for partial nephrectomy using the da Vinci XI surgical system with good accuracy. The technology is easily integrated into the surgical workflow and does not require additional hardware other than a software upgrade. In vivo studies are being planned to further evaluate the technology and its real-world application.

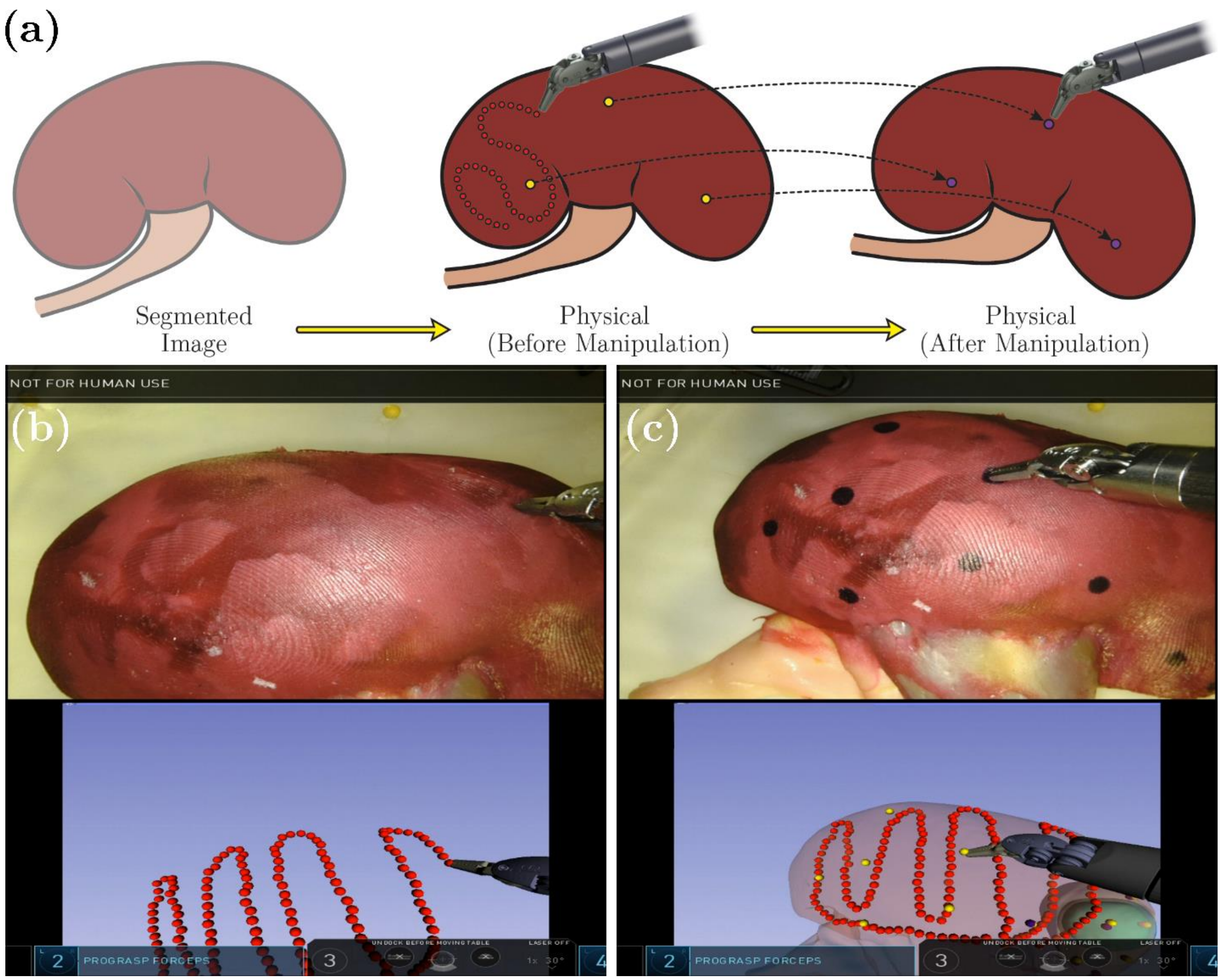

Figure 1: (a) Conceptual illustration of touch-based registration and point-based re-registration. Initial image registration is carried out with a touch-based approach by lightly tracing the kidney surface with the robotic instrument (red dots). Re-registration updates are carried out with a faster point-based approach by touching discrete surgical ink markings placed on the kidney surface (yellow and purple dots). (b) Image guidance display during touch-based registration. (c) Image guidance display during point-based re-registration.

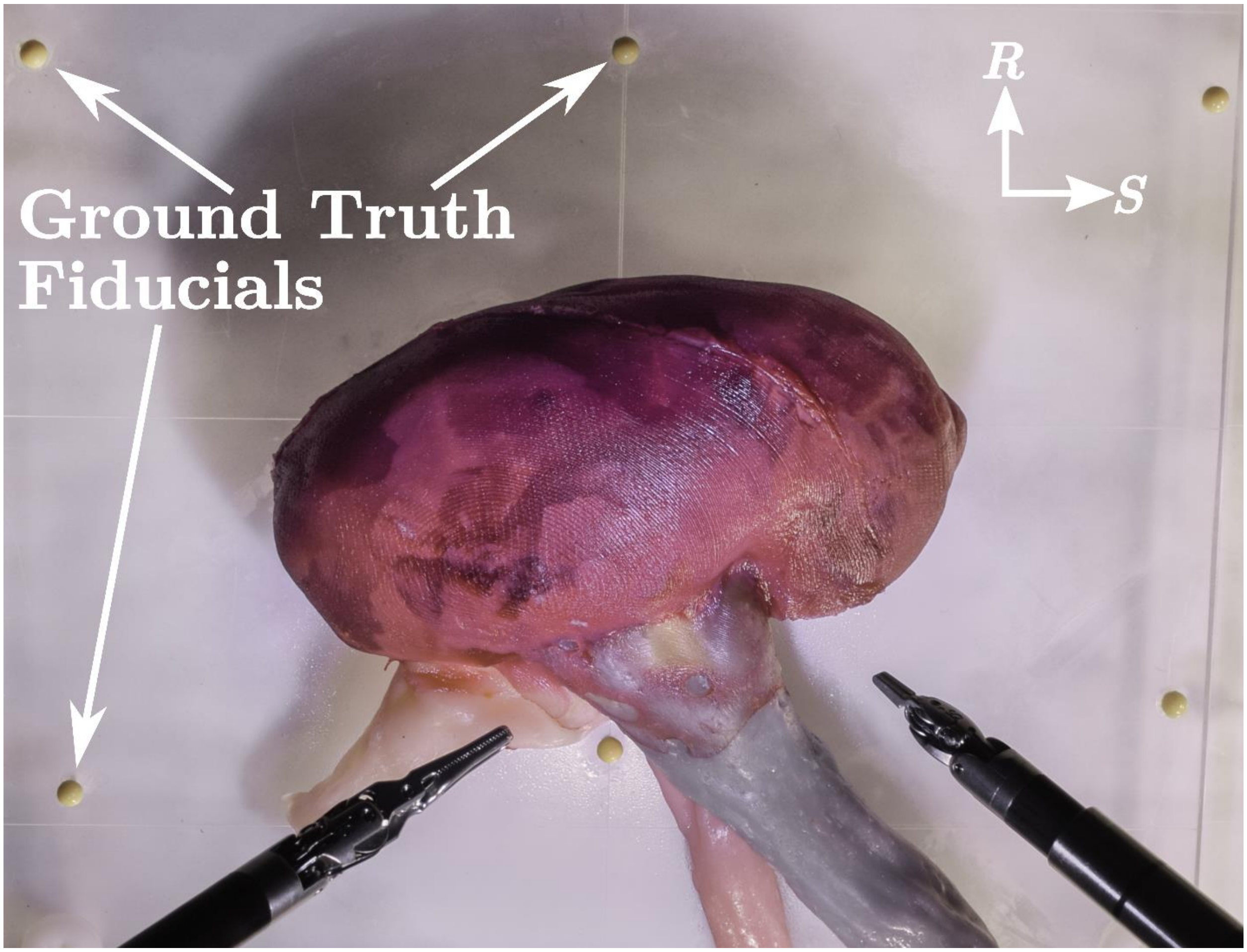

Figure 2: Experimental setup for evaluating registration and re-registration accuracy during simulated partial nephrectomy (R: right, S: superior).

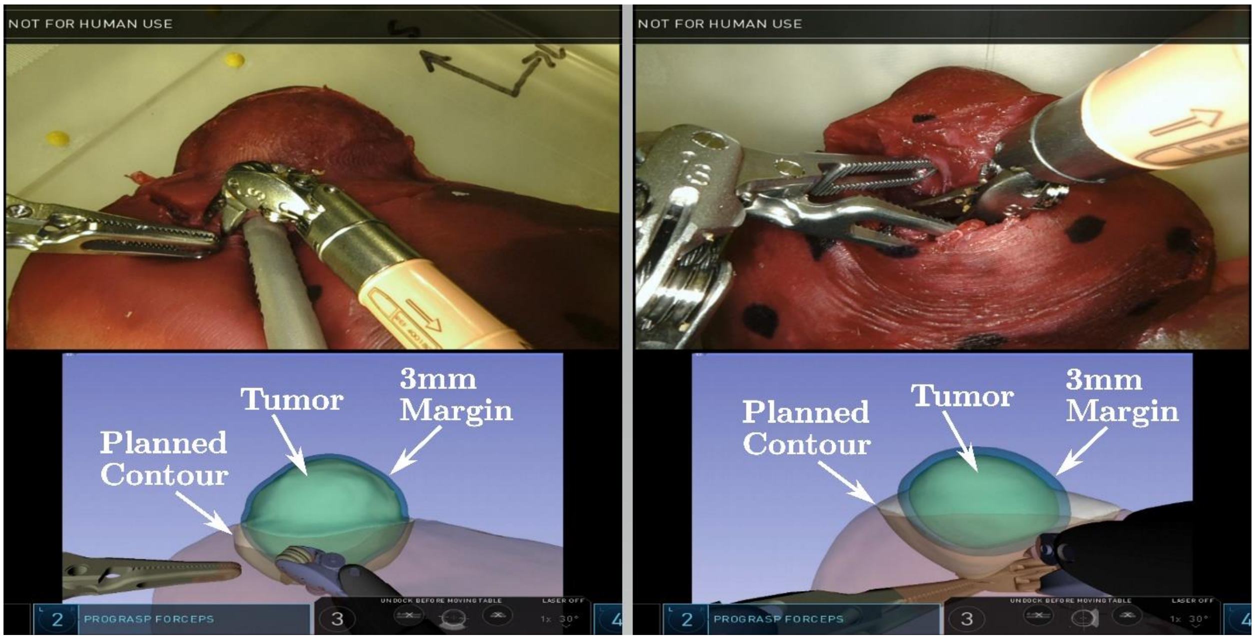

Figure 3: Image-guided tumor resection enabled by our system.

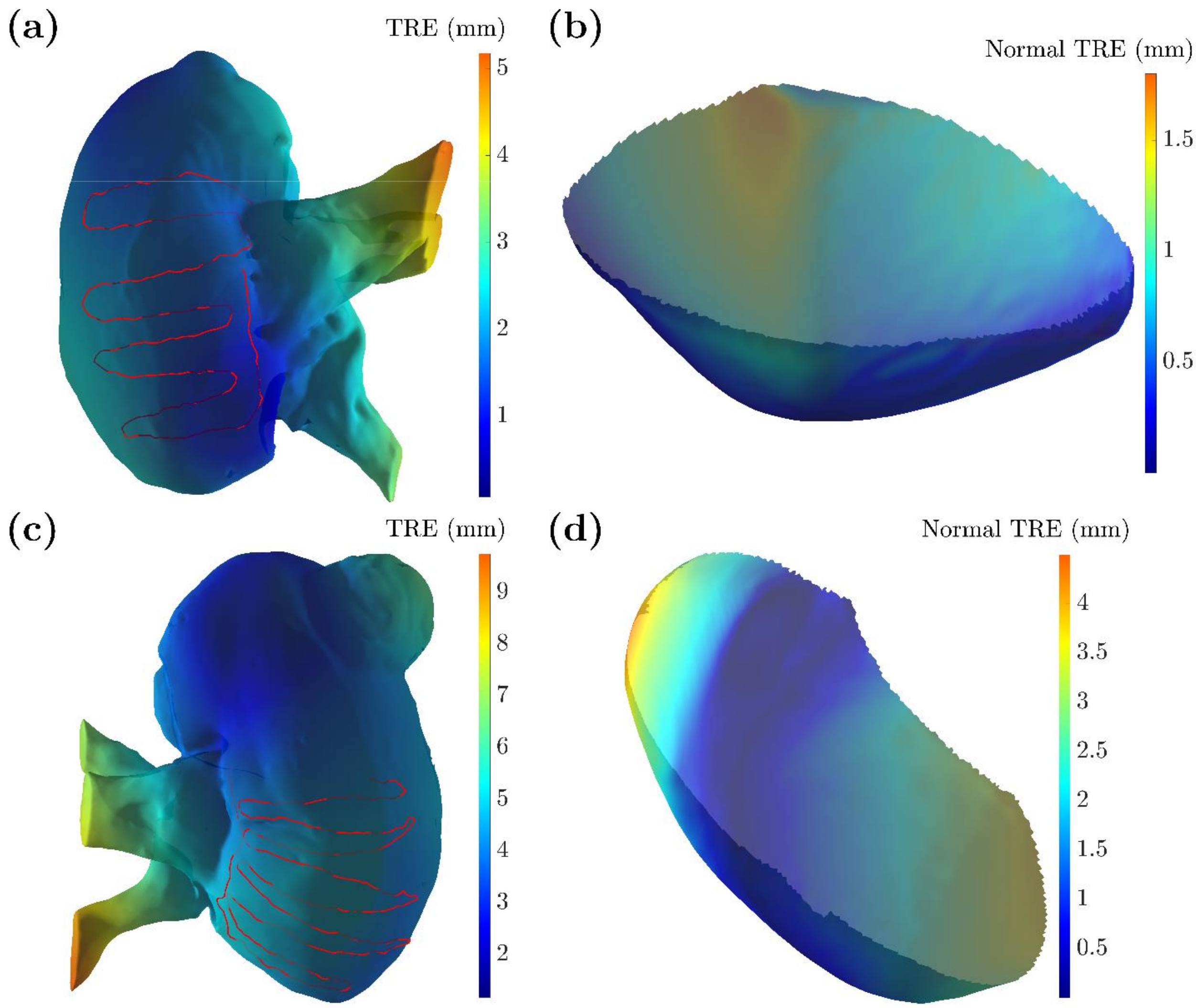

Figure 4: Heat map of target registration error (TRE) after initial touch-based registration. (a) Kidney surface for endophytic case. (b) Planned resection surface for endophytic case. (c) Kidney surface for exophytic case. (d) Planned resection surface for exophytic case.

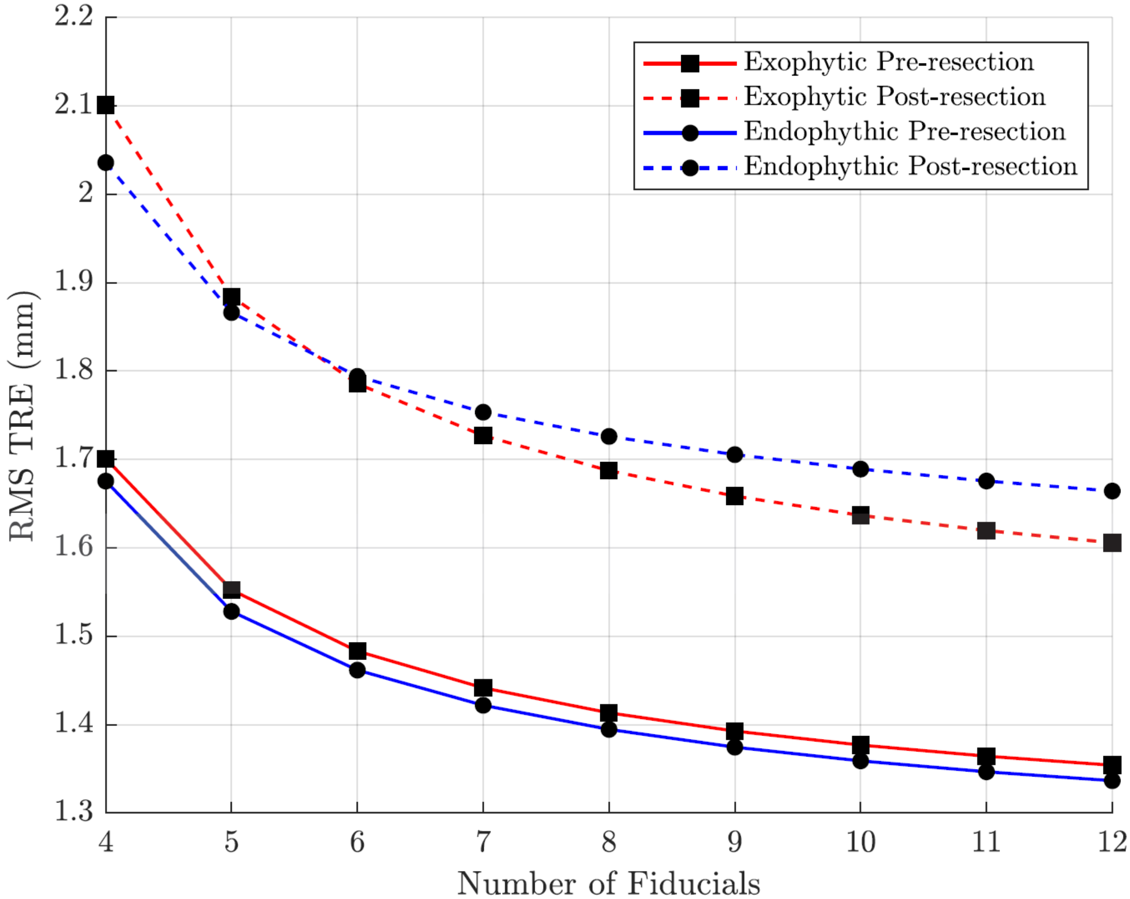

Figure 5: Root-mean-squared (RMS) target registration error (TRE) versus number of ink fiducials used in point-based re-registration. Note that reported error values represent an error in addition to the initial registration error.

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