How Insights from In Vivo Human Pilot Studies with da Vinci Image Guidance are Informing Next Generation System Design

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INTRODUCTION

Using an image guidance system constructed over the past several years [1], [2] we have recently collected our first in vivo human pilot study data on the use of the da Vinci for image guided partial nephrectomy [3]. Others have also previously created da Vinci image guidance systems (IGS) for various organs, using a variety of approaches [4]. Our system uses touch-based registration, in which the da Vinci's tool tips lightly trace over the tissue surface and collect a point cloud. This point cloud is then registered to segmented medical images. We provide the surgeon a picture-in-picture 3D Slicer display, in which animated da Vinci tools move exactly as the real tools do in the endoscope view (see [2] for illustrations of this). The purpose of this paper is to discuss recent in vivo experiences and how they are informing future research on robotic IGS systems, particularly the use of ultrasound.

MATERIALS AND METHODS

In a recent set of in vivo experiments, we deployed our IGS system during robot-assisted partial nephrectomies, using a bystander study protocol [3]. This protocol enables us to test the IGS system without changing the therapeutic process. We do this by using two surgeons, one who solely uses the IGS display to collect data, and one who solely conducts the surgery according to the standard of care without ever seeing the IGS display. This isolates the testing of the IGS system from the therapeutic process, enabling the IGS system to be tested earlier in vivo, to obtain quick data and surgeon feedback on whether various approaches or aspects of the system are likely to be useful to the surgeon. Before conducting our in vivo studies we assessed accuracy in phantoms [1], [2]. Then, to determine whether accuracy improvements translate to the in vivo setting, we performed the following experiments. Surgeons used the da Vinci tool tips to touch (or point the tool jaws at, for subsurface locations) specific anatomical targets, both with and without IGS. Our first observation was that there was error in the pointing process itself, which we

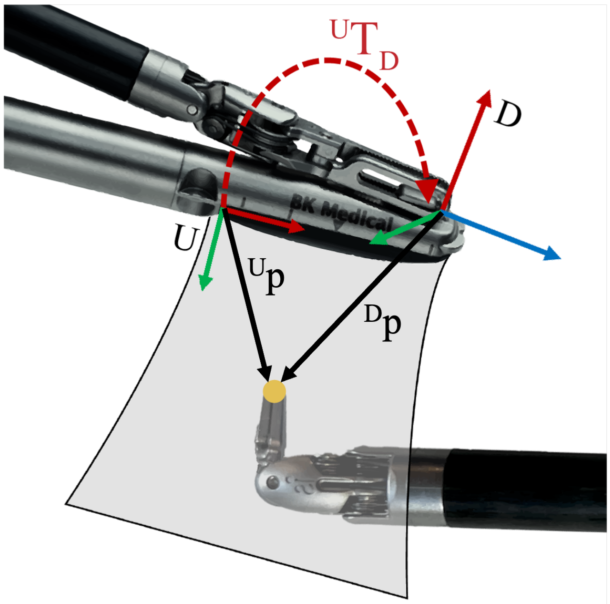

Fig. 1 Proposed hand-eye calibration approach to compute the transformation, $^{U}T_{D}$, between the ultrasound image plane, U, and the da Vinci tool tip coordinate system, D, using the tip of another da Vinci tool.

found we could reduce with a virtual pointer (i.e. a line in the virtual environment that extends the length of the tool jaws) [5]. Overall, our in vivo studies enabled us to quantitatively assess our robotic IGS system in the context of partial nephrectomy, but our results were not statistically significant with respect to demonstrating surgeon accuracy improvement [3]. Note that these experiments were conducted using rigid registration and considered the part of the surgery where the kidney is mobilized from the surrounding fat. Based on these studies, future work will be needed to integrate tissue deformation and cutting models into our IGS system to capture subsequent steps in the procedure.

We saw larger errors at the vein and artery than at the tumor, and these were also larger than we had observed

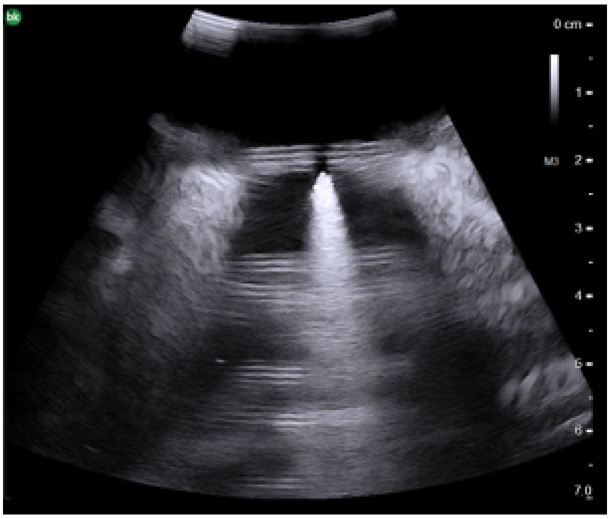

Fig. 2 Example ultrasound image of da Vinci Large Needle Driver tool tip, which provides one calibration point.

in prior phantom studies. These error levels, combined with qualitative observations of tissue deformation during surgery, led us to hypothesize that tissue deformation is responsible.

To address this in this paper, we take the first steps toward the use of intraoperative ultrasound to acquire subsurface points to assist in registration (see e.g. [6]), and inform future tissue deformation models. Our goal is to calibrate the "drop in" ultrasound probe used with the da Vinci robot in a new way, i.e. by placing the da Vinci tool tips of the other arm into the ultrasound image to obtain a set of known points for calibration. This is a robotic adaptation of a technique suggested for use with tracked pointers [7].

Before the ultrasound data can be incorporated into the IGS display, calibration must be performed to determine the transformation between the da Vinci tool holding the probe and the resulting ultrasound image plane (see Fig. 1). Note that this technique eliminates the need for additional calibration phantoms, using the sterilized robotic tool tip that is already present in the surgical scene. Thus it is a practical and efficient solution for the intraoperative hand-eye calibration between the da Vinci Xi and ultrasound image plane.

To perform data collection for calibration the drop-in ultrasound transducer is held by a da Vinci Prograsp tool, via a custom attachment. The tip of a da Vinci Large Needle Driver tool is then repeatedly imaged as shown in Fig. 1, with an example of one of these images shown in Fig. 2. $^{U}T_{D}$ is computed using an iterative least-squares solver which adjusts the parameters in the transformation to minimize the difference between observed robot tip positions in the ultrasound images and those reported by the da Vinci's encoders. After the calibration is complete, a set of points collected the same way, but not used in the calibration process, is used to assess error via the leave-one-out cross-validation approach.

RESULTS

We determined the feasibility of this calibration method by imaging the Large Needle Driver 60 times with the ultrasound probe held by the Prograsp tool. Employing the leave-one-out cross-validation approach, we found the mean target registration error across the 60 data points to be 2.14 mm.

DISCUSSION

Our in vivo pilot studies have revealed significant soft tissue deformation. Based on this, we plan to pursue future tissue deformation models and use subsurface points to augment our current surface-based registration processes. In this paper we have taken a first step toward such a system by addressing the ultrasound calibration challenge. By using the da Vinci's other tool to collect points that are known in both Cartesian and ultrasound image space, we performed a hand-eye calibration. This approach provides a practical method for calibration that does not rely on external tracking systems or a calibration phantom. The average error in our calibrated ultrasound system was 2.14 mm which is in line with the errors observed in past research on ultrasound calibration. This opens the door to future research on use of ultrasound for registration and display of ultrasound images in our IGS system, as well as the creation and incorporation of models for tissue deformation and cutting.

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