Towards Suturing From Within the Urethra Using Concentric Tube Robots: First Experiences in Biological Tissues

Tayfun Efe Ertop\textsuperscript{1}, Jesse F. d’Almeida\textsuperscript{1}, Ernar Amanov\textsuperscript{1}, Jason Shrand\textsuperscript{1}, Naren Nimmagadda\textsuperscript{2}, Shaan Setia\textsuperscript{2}, Nicholas L. Kavoussi\textsuperscript{2}, S. Duke Herrell III\textsuperscript{1,2}, and Robert J. Webster III\textsuperscript{1,2}

Abstract—Towards reducing the invasiveness of radical prostatectomy, we have designed a robotic system for performing it transurethrally. Suturing to attach the urethra to the bladder (i.e. anastomosis) after prostate removal is the most challenging part of the procedure, and has previously been demonstrated robotically only in synthetic phantoms. In this paper, we present initial experiments in biological tissues using ex vivo squid tissue embedded in an anthropomorphic phantom made using 3D printing and silicone casting. We successfully performed running sutures with our robotic system, fastening the urethra and the bladder to one another.

I. INTRODUCTION

Prostate cancer is by far the most prevalent type of cancer among men, with an estimated 248,000 new cases occurring in 2021 [1]. Radical prostatectomy is the procedure typically used to treat higher risk cancers and, over the past several years, the da Vinci Surgical System (Intuitive Surgical, Inc.) has become the most widely used tool for this surgery [2]. Even with the enhanced dexterity of the da Vinci, a significant fraction of patients still experience erectile dysfunction and urinary incontinence post surgery [3]. Survey data show that health-related quality of life (HRQOL) scores of 36.8\% for sexual function and 74.4\% for urinary incontinence after radical prostatectomy [4]. Physicians hypothesize that nerve damage associated with the cutting and retraction required to visualize and mobilize the prostate during the surgery may be responsible for these complications [5].

This has led physicians to attempt a transurethral approach to radical prostatectomy, where a surgical laser is used through an endoscope to resect the prostate [6]–[8]. The surgical procedure is an expanded version of the Holmium Laser Enucleation of the Prostate (HoLEP) technique. Humphreys et al. showed the feasibility of this approach in cadavers [6], canine models [7], and two patients [8]. Humphreys et al. emphasizes that further clinical use of the procedure fundamentally depends on inventing better trans-endoscopic suturing technology for anastomosis [6]. Anastomosis between bladder neck and urethra is needed after the prostate is removed (see Fig. 1). Current tools used for endoscopic suturing such as OverStitch (Apollo, USA) [9] and SR5 suture device (LSI solutions, USA) [6] are not suitable for this task, due to their large size and lack of dexterity.

Concentric tube manipulators provide a means to accomplish this suturing [10]. We initially proposed them as a means to improve HoLEP [11], and then extended the idea in a feasibility study on transurethral radical prostatectomy [10]. Concentric tube manipulators are needle-sized flexible robotic devices made of a collection of pre-curved tubes that can be axially rotated and telescopically extended, resulting in a device that can bend and elongate (see [12] for a review). They have been proposed for use in various minimally invasive endoscopic surgical applications over the years including brain, lungs, and prostate [12]. Using concentric tube manipulators, we initially demonstrated tissue resection with this system in a cadaver prostate [11], and then demonstrated suturing in a synthetic phantom with both the urethra and bladder made from cast silicone rubber [10].

In this paper, we extend these approaches to biological tissues for the first time. We use a squid model which our physician collaborators qualitatively judge to be more similar to human tissues than the initial silicone rubber models. We...
Fig. 2: The overall robotic system during an experimental session. (a) The improved robotic actuation system now incorporates quick-
action brakes to lock endoscope roll, pitch, and yaw (insets (b), (c), and (d), respectively). (e) Our new “hand-switching” delivery channels
enable suturing on both sides of the urethra. The inner lumen that holds the gripper and needle arm delivery channels can rotate about its
axis up to 180° in the endoscope as indicated by the red arrow, hence switching the needle and gripper arms. (f) Photographs of suture
hand-off using the new three-prong end effectors. The plastic clip used for anchoring the suture in tissue is also shown.

successfully conducted an initial proof-of-concept suturing experiment in the squid tissue model. The experimental
design and the results obtained from this experiment are explained in the following sections. Other contributions of
this paper include improvements to the robotic system to increase its ease of use in suturing, including adding locks
to passive degrees of freedom, and a new mechanism for switching the needle arm from the left to the right hand
(or vice versa) and the manipulator arm correspondingly. We also describe the anthropomorphic phantom we created
for the first time, as well as our method of embedding the biological tissues within it for suturing experiments. While
several phantoms have been developed for prostate surgery in the past [13], [14], a reusable, low-cost transurethral phantom
for anastomosis, featuring easy-to-replace squid tissue, has not previously been developed.

II. ROBOTIC SYSTEM

The robotic system described in this paper is an up-
dated version of the system first introduced in [10], which
was used to perform initial proof-of-concept experiments in transurethral anastomosis using a silicone rubber model. The
system delivers two concentric tube robot arms through a 26
Fr resectoscope (27050 SC) with a wide angle lens (27292
AMA Hopkins, Karl Storz, Tuttlingen, Germany) that uses
the same outer sheath currently used clinically. The robot
(shown in Fig. 2(a)) is mounted on a gimbal (for orientation
adjustment) that is suspended from the ceiling. The gimbal
and counter-balance arm enable the surgeon to manually
position the entire robot during surgery. Each concentric
tube manipulator consists of several needle-sized, precurved,
telescopic tubes – each of which are capable of independent
rotation and translation. Each tube is actuated at its base
by DC motors and the curvatures at the distal end interact
elastically with one another. For an overview of concentric
tube robots see [15]. The surgeon controls the manipulators
using 3D space-mice, with a resolved-rates algorithm [16]
used to facilitate task-space operation. The endoscope camera
is also motorized and controlled by the surgeon via foot
pedals. This is an update from [10] in which the endoscope
camera was operated manually.

The procedure for throwing sutures during the anastomosis
is as described in detail in [10]. To briefly summarize, one
manipulator (the ‘needle arm’) is sharpened at the tip to
pierce the tissue, and the other (the ‘gripper arm’) is used
manipulate the suture, urethra and bladder tissue. The
suturing process involves first introducing the suture to the
surgical workspace through urethra while holding it in the
grripper arm. The needle arm then pierces through the urethra
and then bladder, where the gripper arm hands it the end of
the suture. Then, grasping the suture, the needle arm retracts,
pulling the suture through the bladder and urethra walls and
then releasing it. The manipulator arm then re-grasps the
suture and moves it back into the bladder for re-grasping by
the needle on its pass. This process is then repeated as desired
Fig. 3: Pelvic model box. (a) Segmentation of anatomical parts from the MRI scan (b) The bladder model suspended on the 3D printed post with elastic bands to mimic the remaining attachments of the human bladder after prostatectomy (c) Photo of the assembled box to create a running suture. Note that the use of barbed suture means that no knot must be tied at the end of this process to keep the suture tensioned.

To facilitate suturing efficiency, we made several improvements to aspects of the system’s mechanical design. First, we included locks on each degree of freedom of the gimbal mechanism (see Fig. 2(b)-(d)) as well as the counterbalanced support arm that enables the physician to easily position the robot during surgery. These locks enable the physician to hold the position of the robot after reaching the anastomosis site, while manipulating the concentric tube manipulators to perform suturing. We also included a new mechanism to enable the surgeon to “switch hands”, moving the needle arm to the left or right hand side of the endoscope, to facilitate easy suturing on the left or right hand side of the urethra (see Fig. 2(e)). This mechanism is operated by a lever at the base of the endoscope attached to the inner lumen of the endoscope, which rotates the channels that carry the needle and manipulator arms through the endoscope. Additionally, we switched to using 50 mm long barbed V-Loc sutures (V-Loc™180 3-0, Medtronic, Minneapolis, MN, USA) along with plastic clips for anchoring the suture in the tissue. Lastly, we included new three-prong graspers for manipulating suture and tissue at the tips of the concentric tube manipulators, as shown in Fig. 2(f).

III. EXPERIMENTS

The experimental setup used in this study can be seen in Fig. 2(a). The surgical phantom used for the experiments consists of a pelvic model designed to be reusable. Biological tissue samples to represent the urethral stump and the bladder can be placed in this model, and can be removed after the experiment. To create the pelvic model, we began by segmenting pelvic muscle, hip bones, and the bladder, prostate, and urethra from a human MRI scan (see Fig. 3) using 3D Slicer [17]. The segmented prostate was removed from the model before fabrication of the various structures. To create pelvic bone models we used PLA 3D printing (Stratasys, USA). The soft tissue components of the pelvic muscle and urethra were cast in silicone, using molds made from 3D printing using the same printer and material used for the pelvic bones. The very end of urethra (the side facing the bladder) was tapered to accommodate the attachment of squid tissue. A holder for simulated bladder tissue was similarly made using 3D printing. The natural compliance of the residual bladder attachments after prostatectomy was represented using rubber bands to suspend the tissue fixture,
TABLE I: Concentric tube robot parameters for the needle and gripper arms used in the experiments. OD and ID refer to outside and inside diameter of the superelastic Nitinol tubes, respectively. κ is the curvature that is shape-set into the tubes. \( L_s \) is the length of the straight tube section, and \( L_c \) is the length of the curved tube section. All tubes have circular cross-sections.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Outer Tube</th>
<th>Inner Tube</th>
</tr>
</thead>
<tbody>
<tr>
<td>OD (mm)</td>
<td>1.40</td>
<td>1.18</td>
</tr>
<tr>
<td>ID (mm)</td>
<td>1.25</td>
<td>0.89</td>
</tr>
<tr>
<td>( \kappa ) (m)(^{-1})</td>
<td>0</td>
<td>54.0</td>
</tr>
<tr>
<td>( L_s ) (mm)</td>
<td>106.4</td>
<td>120.9</td>
</tr>
<tr>
<td>( L_c ) (mm)</td>
<td>0</td>
<td>43.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Outer Tube</th>
<th>Inner Tube</th>
</tr>
</thead>
<tbody>
<tr>
<td>OD (mm)</td>
<td>1.80</td>
<td>1.18</td>
</tr>
<tr>
<td>ID (mm)</td>
<td>1.61</td>
<td>0.89</td>
</tr>
<tr>
<td>( \kappa ) (m)(^{-1})</td>
<td>52.5</td>
<td>58.7</td>
</tr>
<tr>
<td>( L_s ) (mm)</td>
<td>41.8</td>
<td>54.6</td>
</tr>
<tr>
<td>( L_c ) (mm)</td>
<td>33.3</td>
<td>33.6</td>
</tr>
</tbody>
</table>

as shown in Fig. 3. Lastly, prior to experiments the entire setup was placed into a clear plastic box that was filled with water. This was done to represent the transurethral surgical environment, in which the urethra and bladder are typically filled with water. Water was circulated using a pump, to simulate the circulating flow used in clinical prostate procedures.

The biological tissues used in these experiments were harvested from small squids, and cut to the specific shapes needed. Squid was selected due to its natural luminal shape, and tissue properties that are, in the opinion of experienced surgeons, qualitatively similar to human tissues for purposes of endoscopic manipulation and suturing. The squid was prepared as shown in Fig. 4. The squid samples were washed and dyed red using food coloring to enhance visual similarity to human tissue. The squid tissue representing the urethra was attached to the silicone urethra using sutures as shown in Fig. 4, with approximately 10 mm extending beyond the silicone for suturing. The tissue representing the bladder was made by cutting the squid tissue into sheets and placing one on the front and one on the back of the 3D printed bladder box (see Fig. 4). Only the squid tissue on the front of the bladder was used for suturing, but we desired an enclosed bladder, with tissue at the distal end, to visually simulate the clinical environment.

The concentric tube robot parameters for both arms used in the experiment are shown in Table I. Note that this parameter set has not yet been optimized, and such optimization is the topic of future work.

IV. RESULTS

The robot and phantom described above were used to successfully pass 5 sutures through the urethra and bladder to perform an anastomosis. The operation started by deploying the endoscope through the urethra. Suture was carried to the surgical site simultaneously with the endoscope using one of the concentric tube manipulators. Suturing then proceeded according to the suturing pattern described in [10]. Hand switching occurred half way through, with three sutures placed on the left-hand side, and two on the right-hand side, of the urethra. The final anastomosis is shown in Fig. 5(b).

V. CONCLUSION

This paper describes initial experiences performing anastomosis with a concentric tube robot system in a urethra and bladder model made from biological tissue. We described several changes made to robotic components to improve system usability. We also described a reusable anthropomorphic phantom that facilitates suturing experiments. We were successfully able to throw sutures in a biological tissue model of the urethra and bladder, entirely transurethrally and robotically. This experiment demonstrates the feasibility of performing anastomosis in biological tissues.

However, much work remains before these results can be translated to the clinic. There is room for optimization of concentric tube manipulator design parameters for enhanced dexterity, exploration of the optimal number and locations of the sutures deployed, optimization of grasping end effectors, and even the possibility of other suture patterns including interrupted sutures. But what is clear from the results in this paper is that sutures can be delivered and deployed in biological tissues through an endoscope with concentric tube
manipulators. Thus, the feasibility experiments in this paper represent a promising step toward reconstructive suturing within the urethra. This, in turn, promises to enable less invasive prostatectomy in the future, which will improve rates of post surgical sexual function and urinary continence, if surgeons’ hypotheses are proven correct.

REFERENCES


