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A Novel Surgical Robot Design: Minimizing the Operating Envelope Within the Sterile Field

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Abstract—**Current surgical robotic systems dominate the space in the sterile field above the patient. Ideally, next generation systems will couple the simplicity of traditional laparoscopic instruments with the dexterity of robotic assisted surgery. This paper presents the design of a novel 6 DOF robotic instrument that eliminates the dependence on pivoting about the incision point. The motion envelope of the proximal end of the tool is therefore constrained to a line rather than the typical cone. This reduction in size enables better access to the patient and allows standard minimally invasive hand tools to be used alongside the robot.**

I. INTRODUCTION

Teleoperated surgical robots are the way of the future, but current first generation systems do not make economic sense for most procedures. At present, the daVinci System from Intuitive Surgical is the only commercially available robot on the market [1]. Its $1.5 million price tag is prohibitively expensive for the majority of hospitals. This fact, coupled with high per procedure costs, significant setup times, and the requirement of a dedicated staff and operating room have limited its adoption [2].

Additionally, significant drawbacks exist with respect to the mechanical realization of the daVinci. The design of the robotic instruments are based upon the traditional laparoscopic surgery paradigm, wherein straight rigid tools are maneuvered through small incisions by the surgeon moving the instrument handles outside the patient's body. In current robotic surgery, the instruments use the same trocar kinematics and pivot about the incision point using a remote center of motion configuration. The corresponding structure necessary to achieve this motion must be substantial because it has to move the proximal end of the instruments over a large distance to achieve the desired range of motion. Consequently, the robot takes up a significant portion of the sterile field and limits assistant surgeons' ability to work alongside the robot.

For robotic surgery to succeed economically, systems must be developed that are easily integrated into the operating room and require minimal overhead. The ideal system should couple the ease and relatively low cost of traditional laparoscopic instruments with the dexterity and functionality of robotic assisted surgery. This paper details the development of a new robotic instrument design that eliminates the dependence on pivoting about the incision point and occupies a minimal volume in the OR and sterile field.

Fig. 1. New robotic instrument design with articulated elbow joint inside patient body cavity

Fig. 2. The daVinci system during an actual urology procedure. Access to the patient is severely limited by the mechanism in the sterile field over the patient.

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II. BACKGROUND

The new instrument design presented here is an evolution of the Laprotek surgical robot produced by EndoVia Medical. Laprotek was designed to compete with the daVinci and be a cheaper (target price of $250k) and less OR intrusive alternative, thus making robotic surgery more practical and economically feasible [3]. Although EndoVia is now out of business, the Laprotek has been clinically validated on humans and used to perform 10 robotic cholecystectomy procedures.

The Laprotek design made several improvements over the daVinci. As can be seen in Fig. 3 the slave instrument "motor packs" (weighing 5 kg each) are mechanically mounted on the existing bedrails of the OR table. The motions from the motors are transmitted to the surgical instruments via stainless steel cables that run through the length of the tools. This design simplifies setup and greatly reduces the size and weight of the system compared to the daVinci's large instrument platform that holds and maneuvers the robotic tools.

Paramount to the exterior space-saving nature of the Laprotek system is the novel design of its instruments. Whereas the daVinci system uses a straight tool and moves the back end of the tool through a full three dimensional cone, the Laprotek system utilizes a curved "guide tube" to position the tools within the patient. This approach allows the tool to be positioned by moving the proximal end of the tool only in a plane. The other degree of freedom, which would typically be actuated by moving out of this plane, is instead achieved by rotating this curved guide tube. This solution sweeps out a much smaller volume in the sterile field, thereby minimizing collisions between the instruments, camera, and other standard laparoscopic tools.

Another key feature of the Laprotek is its modular system architecture and software. The surgeon console contains the electronics, computer, and two 6 DOF control arms with haptic feedback capability. The mechanical instrument arms are coupled to the motor packs through a quick connect mechanism. The new tool design described in the following section uses these components as a platform for its actuation and control.

Fig. 3. Laprotek system with instruments mounted to OR table.

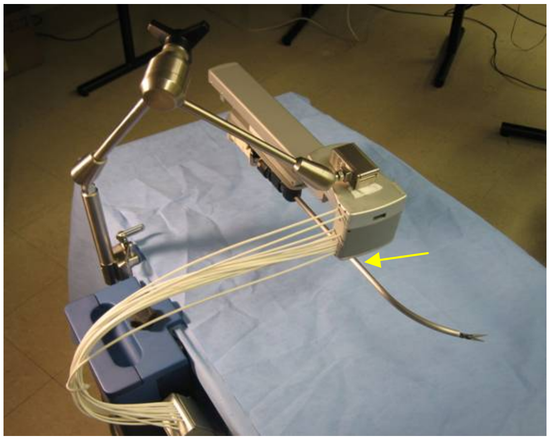

Fig. 4. Laprotek tool and support structure. The stainless steel guide tube serves to move the distal end of the instrument up and down while the back end can pivot about the incision point. The arrow indicates the location of the surgical port.

III. NEW TOOL DESIGN

The primary design parameter for the new tool is that the motion outside the patient be constrained to a line rather than a cone like the daVinci or a plane like the Laprotek. To achieve full 6 DOF dexterity in the absence of the external pivoting motion, two joints were moved inside the body. This particular design has several distinct advantages.

1) The exterior working volume is minimized. The complications regarding collisions between tools and interference with assistant surgeons due to suboptimal tool positioning is all but eliminated.

2) Since the tools are not constrained to pivot about the incision, the instruments are easily positioned and can be moved like traditional hand tools and locked in place. Robotic dexterity can then be used over the tool's interior dexterous range of motion.

3) Complex external supports and mechanisms are greatly reduced. All that is needed is a mechanical support arm to hold the linear track on which the tool travels.

4) There is no remote center of motion mechanism, which means that the tool's actuated inertia is considerably lower, thus making force reflection to the master more realizable.

The mechanical realization of the tool is represented in Fig. 5 below. The 10mm diameter device consists of a translating and rotating joints on the proximal end outside the body (joints 1&2), elbow and axial rotation joints inside the body (joints 3&4), and a typical 7mm diameter surgical robotic wrist on the distal end, like that found on the Laprotek instruments (joints 5&6). The novel part of this design is that joints 3&4 take the place of the exterior degrees of freedom typically actuated by pivoting about the incision point.

All of the degrees of freedom are actuated using stainless steel cable tendons. Cables pass from the mechanical coupler on the motor pack through tightly wound spring conduits with Teflon liners to the body of the instrument.

The linear slide (joint 2) has a range of ± 75 mm and can produce a force of 40 N. The base rotation joint (joint 1) has a range of ± 180 degrees but is software limited to ± 75 degrees. This joint has a maximum torque of 1.4 N-m, resulting in a tip force of 26 N with joint 3 at 45 degrees and the length between joints 3 and 6 at 75 mm.

The instrument's elbow joint (joint 3) is manufactured from 303 stainless steel and designed with miniature ball bearings supporting the shaft. Force is transmitted from the cable to the distal end of the joint via an 8mm pulley that is pinned to the shaft that runs through the joint. Eight cables pass through the joint to actuate the four distal joints. The cables that actuate joint 4 lay on the shaft of joint 3 and thus effectively use it as a pulley. The other six cables that actuate the wrist and jaws run through conduits made from PEEK tubing, a thermoplastic with high lubricity and high axial rigidity. The elbow joint has a range of motion of ± 90 degrees, however it is limited in software to operate away from the straight position to avoid a singularity.

The primary design consideration for the elbow joint is to achieve the 22 Newtons of tip force suggested in [4]. The pulley is therefore sized to be as large as possible (8 mm) while still fitting in the 10 mm instrument. Unfortunately, even with this pulley, only a 13 N tip force is achievable through the elbow joint, limited by the 267 N breaking strength of the cable. A new elbow joint is under development that uses a four bar linkage design to double the amount of achievable tip force.

Joint 4 is comprised of a nylon exterior shell created using selective laser sintering (SLS) with two bearings and a concentric hollow stainless steel shaft glued into it. Actuation cables come through the proximal end of the shell through curved guides created during the SLS process and wrap around this shaft, thus transforming the axial translation of the cable into axial rotation of the joint. The maximum torque of this joint is 0.62 N-m, as defined by the 178 N break strength of the cable. The range of motion is ±180 degrees. While the nylon used for the joint is USP level VI biocompatible, a finished device would likely be made completely from stainless steel for improved strength.

The wrist and jaws (joints 5&6) are a pitch-yaw design. The maximum torque in these joints is 0.53 N-m, again defined by the cable break strength of 178 N. The wrist can rotate ± 90 degrees and each jaw ± 90 degrees. Torque feedback through the haptic interface is used to keep the surgeon from passing through the singular point caused when the wrist is near ± 90 degrees.

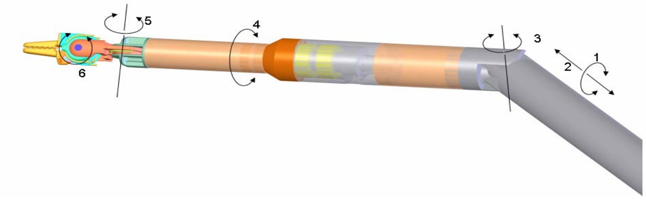

Fig. 5. Schematic representation of new tool design demonstrating the 6 degrees of freedom of the instrument

In order to avoid singularities and stay within the maximum effective working range of the tool, joint 3 is limited to move between 15 and 85 degrees from straight. The tool's best operating region is when joint 3 is in the neighborhood of 45 degrees. There are several configurations that allow the joint to be in this optimal configuration. Fig. 6 demonstrates how the tool can be used to get into tight spaces, such as for a robotic radical prostatectomy, as well as how the tools can be used to maneuver around organs or other obstacles, a technique that is not possible with today's technology.

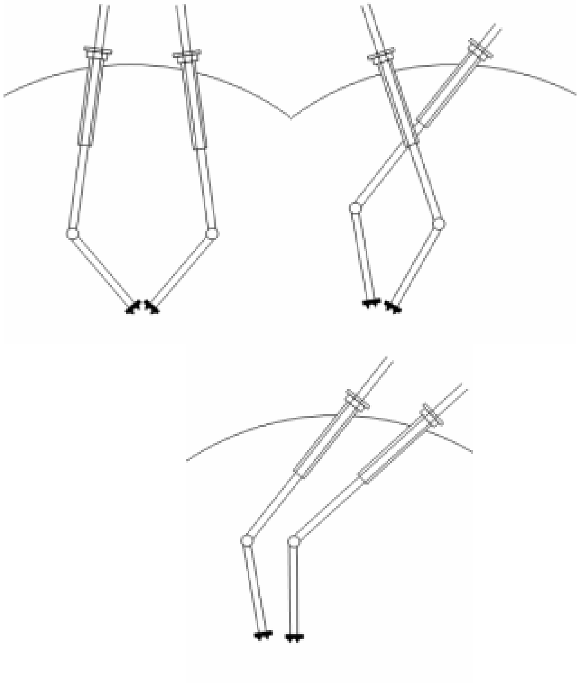

Fig. 6. Possible configurations for instruments. The top left image shows a standard configuration, the top right shows a configuration that allows the tools to get into a narrow space, and the bottom shows how the tools can manipulate around obstacles.

A potential disadvantage of this design is reduced working volume inside the patient. However, many procedures require a high degree of dexterity in a limited volume. For example, Fig. 7 shows a possible configuration of the tools in a radical prostatectomy, one of the most common surgical procedures performed with robots [5].

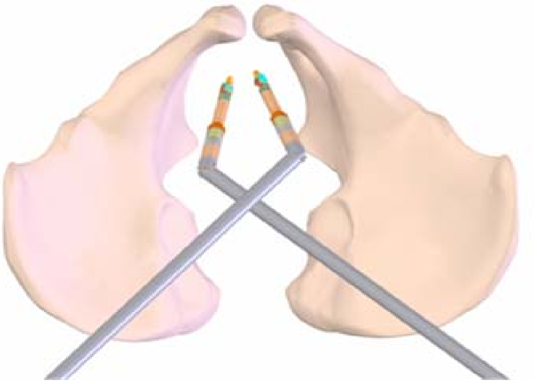

Fig. 7. Possible instrument configuration for radical prostatectomy

A distinct advantage of the new tool design is the simplification of surgical port placement. Experience has shown that robotic surgery with the Laprotek and daVinci is very sensitive to surgical port placement. Cannon, et al. have even developed a specific procedure to find the optimal position for the port to maximize performance [6]. Since the instrument described here does not pivot about the incision point, ideal port placement is less critical for success, and port placement optimized for standard laparoscopic tools will suffice. This is beneficial since a standard minimally invasive case could easily be converted to a robotic case if the procedure is more difficult than expected.

Robotic instruments that move more degrees of freedom inside the body translates directly to an idea that has yet to be realized in any fashion in robotic surgery: non straight or specialized tools that can be tailored to specific procedures. For example, the length of the link between joints 3 and 5 can be changed from its current length to shorter lengths for more precise procedures that do not require as extensive dexterous range of motion. Additionally, the support tube between joint 2 and joint 3 can be made in different bent shapes for specific surgeries, possibly allowing the surgeon to choose a tool based on anatomically ideal port placement rather than placing ports based on the constraint imposed by a straight laparoscopic tool.

IV. RESULTS

Fig. 1 shows the prototype of the new instrument assembled and attached to the Laprotek motor pack. The inverse kinematics software has been developed and tested and the joints function as expected. We have been able to drive the tool using the Laprotek master console and are currently optimizing its performance with respect to cable slack and singularity avoidance issues.

The primary problems currently being addressed are cable routing and mechanical advantage of the elbow joint. Cable routing is being further developed with the design of pulley and guide systems. PEEK cable conduit, while acceptable in the flexible part of the Laprotek tool, has proven to be unsuitable for this design because of the length and tight bending radii required. The tubing also has a tendency to kink in the elbow joint and compresses axially under load, causing it to form a helix around the stainless steel cable. Friction results from this deformation, causing a nonlinear response and loss of force at the tool tip. We are developing future generations of this design to rectify these problems.

V. CONCLUSION

Surgical robots are in their infancy and have tremendous potential to transform the way surgery is performed. Cost effective solutions must be developed that make economic sense. Next generation robotic surgery must be simpler to perform and not be an event in and of itself. The new instrument design described in this paper is a step in that direction.

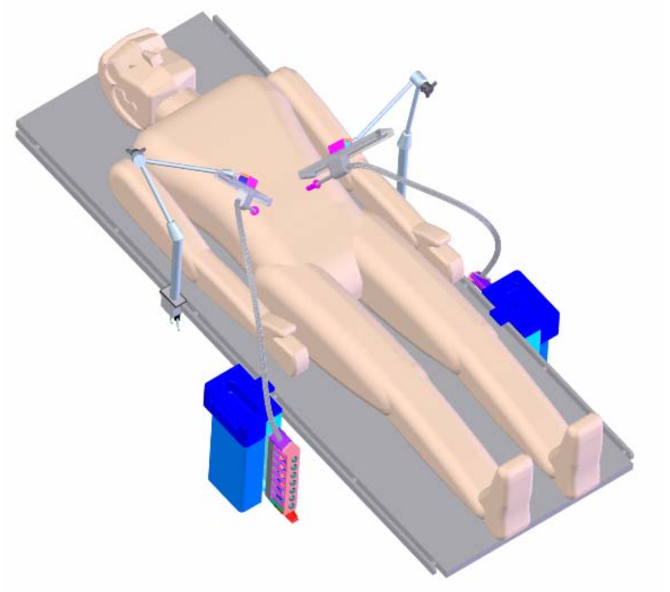

Fig. 8. New tool in operating room context. The smaller working envelope allows easy access to the patient. Additionally, the small volume occupied brings the potential for placing the master in the sterile field, thus allowing the surgeon to easily translate between hands on and robotic surgery.

Minimizing the required volume in the sterile field has the distinct advantage of allowing assisting surgeons unimpeded access to the patient. Fig. 8 demonstrates the minimal space required for this design. Surgeons can then easily use standard specialized laparoscopic tools such as staplers and clip appliers simultaneously with the robot. Instead of using a robot to do every surgical task, we believe that a surgical robot should be used to do that for which a robot is best suited: operate with a high degree of precision and dexterity in areas that cannot be otherwise accessed using traditional laparoscopic tools.

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