Robotic Hand-Held Surgical Device: Evaluation of End-Effector's Kinematics and Development of Proof-of-Concept Prototypes

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Abstract. We are working towards the development of a robotic hand-held surgical device for laparoscopic interventions that enhances the surgeons' dexterity. In this paper, the kinematics of the end effector is studied. Different choices of kinematics are compared during an evaluation campaign using a virtual reality simulator to find the optimal one: the Yaw-Roll (YR) kinematics. A proof of concept prototype is made based on the results.

1 Introduction

Minimally invasive surgery (MIS) causes less operative trauma and leaves patients with less pain and scarring, speeds recovery, and reduces the incidence of post-surgical complications. Conventional instruments used in MIS are hand-held instruments with long shafts, an end effector (needle holder, dissector etc.) at one end and a handle at the other. The instrument motion is constrained at the pivot point to 4 degrees of freedom (DOF): (1) translation along the shaft of the instrument, (2) rotation around the translational axis and (3) and (4) limited inclination of the shaft pivoted trough the incision [1]. Some gestures are very difficult or impossible to make using the non-dexterous conventional instruments. One could imagine a more dextrous device with a jointed end effector adding one or more DOF. The end effector must have at least 6 DOF to allow the surgeon choose the orientation and position of the end effector arbitrarily. The DOF added to the end-effector could be actuated manually, pneumatically or electrically. The latter gives a mechatronic (robotic) hand-held instrument. But making such a miniature-scale instrument with a mechanical force transmission system that can provide for the requirements in MIS, is difficult and costly. So, choosing the simplest kinematics for the added DOF that allows performing all needed movements is critical. In [2] for example, the end-effector can yaw or pitch while the surgeon can roll the instrument's shaft using his thumb. [3] has

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an end-effector that can yaw, pitch and roll, but its shaft's rotation is manual and thus limited. In [4], the end-effectir can yaw and roll. The *da Vinci* surgical system [5] has end-effectors that can yaw, pitch and roll. All these instruments however, have 10 mm thick shafts. Surgeons on the other hand, demand 5 mm instruments for better integration in Single-access or NOTES operations. In this paper we explain our efforts towards the development of a robotic dexterous hand-held instrument for laparoscopy with a 6 mm shaft.

2 Simulation

To evaluate and compare different handles, control modes and kinematics, we made a virtual reality (VR) simulator. Fig. 1(a) show the simulator.

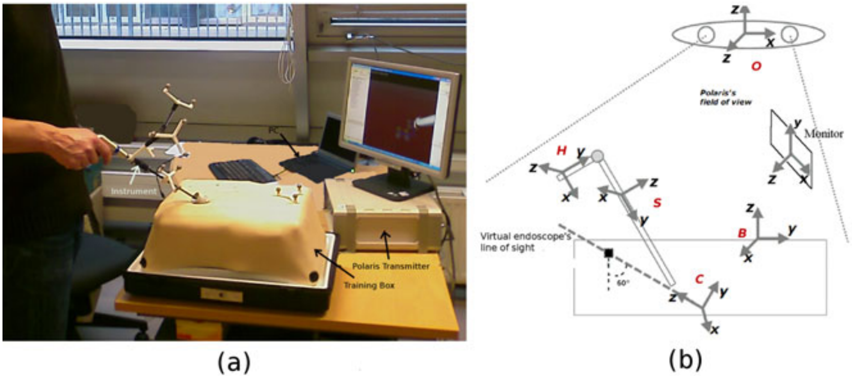

Fig. 1. (a) Simulator in use, (b) Local coordinate systems of the simulator

Polaris, a motion tracking system, keeps track of the position and the orientation of each rigid body in the scene: the training box and the instrument (a Polaris target with a local coordinate system is attached to each of them). Fig. 1(b) shows different coordinate systems present in the scene. The surgical instrument consists of a shaft and a finger-operated handle, (we used a Nunchuck^{TM} from a Wii video game console). The handle has a 2 DOF joystick under the thumb and 2 buttons under the index finger. The kinematics of the instrument's virtual end-effector can be programmed in the simulator. A 19" LCD monitor is used to show the simulated endoscopic image of the inside of the training box. It is positioned 1m away from the operator and deviated 45° from his line of sight to resemble the situation in an operation room. The control program runs on a PC. The pose of each body is calculated in the virtual endoscope's coordinate system. This virtual endoscope's position on the training box, its line of sight and its scope can be chosen arbitrarily. We chose a triangle with 10 cm sides to place the instrument and endoscope, a line of sight inclined 60° from vertical and a 75° scope. The virtual image of the inside of the box is finally rendered using the OpenGL 2.0 library. There is no force feedback, but a visual feedback that indicates collisions between the needle and the working surface. The image shows the instrument with its end effector holding a needle, and a working surface with a grid and suturing points identified by different colors. Fig. 2 shows suturing in the simulated scene. Evaluations are based on subject performance in making sutures. One of the main advantages of a dexterous surgical device is considered to be its ability to make sutures in difficult angles e.g. sagittal sutures. Our simulated suturing task includes putting the needle in the right orientation so as to insert it in the working surface with the right angle, reaching the suture point and turning the needle to bring it out of the exit point. This is considered the end of the gesture. This series of motions (orient, reach, orient) was chosen based on previous studies done on decomposition of laparoscopic tasks [6], [7].

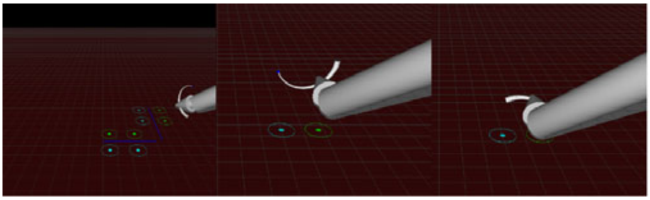

Fig. 2. From left to right: snapshots from the simulated scene showing a suture

2.1 Evaluation of Different Kinematics for the End-Effector

Reduced Set of Kinematics. Our objective was to compare different kinematics for the end effector and choose the optimal one. Surgeons need to be able to suture in different angles (frontal/sagittal). As a result they need 6 DOF needle holders. Using more than 6 DOF makes the task of visumotor control more difficult for the operator. It would not be possible to control the end-effector in its working space either, as 4 of the DOF are exclusively controlled manually. The question we are studying here is which 6 DOF kinematics is the best one for a hand-held laparoscopic instrument, knowing that 4 DOF are already defined as a result of the instrument being constrained by the pivot point. Keeping the already existing 4 DOF, we should add 2 more DOF to the end effector. The 2 DOF we want to add, are those of a 2 DOF wrist added to the end-effector. Without loss of generality, we suppose that the 2 revolute joints of the wrist have concurrent axes. For 2 revolute joints with concurrent axes, 6 combinations of rotational axes are possible. These combinations are: pitch-yaw, pitch-roll, yaw-pitch, yaw-roll, roll-pitch and roll-yaw. But pitch-yaw is the same as yaw-pitch if we only turn the shaft 90°. Pitch-roll and yaw-roll are also the same. Roll-pitch and roll-yaw are singular combinations. This leaves us with 2 possible combinations: yaw-roll (YR) and yaw-pitch (YP). The rotation of the instrument around its longitudinal axis is normally manual. Surgeons have to rotate their whole arm to rotate the instrument and still, the rotation is limited. So we decided to make this rotation automatic as well, giving subjects the ability to rotate the shaft clockwise and counter clockwise using 2 buttons. Another possibility we thought about was to add another DOF to the wrist to make it a 3 DOF wrist (like [3] and [5]). Again, there are 6 possible combinations of 3 concurrent rotational axes. 2 of them are singular (RYP and RPY). The other 4 are become the same from the operator's point of view just by rotating the device and are equivalent to a YPR kinematics. A 3 DOF wrist makes the total number of DOF 7, with 3 of them controlled by fingers. The rotation of shaft stays manual. So the total possible kinematics for 2 and 3 DOF wrists with concurrent axes are reduced to 3 kinematics: YP, YR and YPR, shown in Fig. 3.

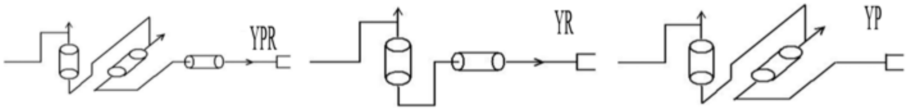

Fig. 3. 3 kinematics for end effector wrist

Evaluation Methodology and Metrics. For each evaluation, we asked test subjects to do frontal and sagittal sutures on a horizontal virtual working surface inside the training box. The suture points were identified by different colors. The subjects were engineering students with no experience in laparoscopy. Literature suggests that expert laparoscopic surgeons are significantly different from surgical novices in terms of applied forces and torques [8], [9], patterns of movement [10], task completion times [8], [9], [11],[10], trajectory length [10] and number of errors [12]. However, these studies that are mostly done for the purpose of modeling surgical gestures in laparoscopy and providing metrics for objective assessment of skills in virtual reality simulators, are done using either conventional laparoscopic instruments with 4 DOF or the da Vinci surgical system. When it comes to instruments with novel human-robot interfaces and different kinematics, expert surgeons are probably not greatly different from novices. In fact, the additional DOF and the method of controlling them may be as new to them as it is to the novices. As a result, surgeons and novices will both use their basic visumotor skills to execute the new tasks. This strongly suggests that the results of our studies would be the same, had we used expert surgeons as subjects. This has of course to be proven with experimental data in a separate study using expert surgeons as subjects. Besides, it is not even sure that expert surgeons do better than novices with these novel instruments as they do with conventional instruments or the da Vinci. For example, there is evidence that playing video games could improve surgical skills in minimally invasive surgery [13], [14]. Younger subjects though surgically novice, have generally more experience with video games and the joysticks used to play them than middle age expert surgeons.

The metric used in the evaluations is the time to completion of task (TCT). [15] states that the TCT is a practical, easy and valid objective tool for assessing acquired technical skills of urology trainees in a laparoscopic simulated environment. It is also used for comparing different surgical instruments for laparoscopy [16]. Each user made 5 frontal and 5 sagittal sutures using each of the kinematics and his average TCT for 1 suture was calculated.

Results and Discussion. Fig. 4 shows the average TCT for each of the 15 subjects. Table 1 shows the mean TCT of all subjects for each of the 3 kinematics tested. The results show that the YR kinematics is slightly better than the YPR kinematics, and both of them are largely better than the YP kinematics, in terms of TCT. Only 3 out of 15 subjects were able to make sutures with the YP kinematics in the 3 minute per suture time limit. From the evaluation results of different kinematics for the end effector, we could see that an end effector able to yaw and roll results in the least TCT for suturing. Technologically, it is much more affordable to make a 2 DOF mesoscale wrist than a 3 DOF one. At the same time, it is dexterous enough to allow suturing in different angles. The YR kinematics of the end-effector plus rotation of the shaft, give surgeons 6 DOF instruments.

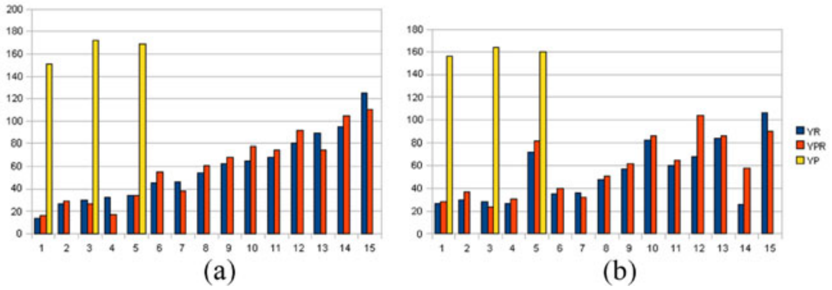

Fig. 4. Average TCT in seconds for 15 subjects using 3 different end effector wrist kinematics

Table 1. Mean time to completion for YR, YP and YPR kinematics in seconds

	Frontal	Sagittal
YR	57.73	58.67
YPR	52.4	58.33
YP	$>> YR, YPR$	$>> YR, YPR$

3 Mechanical Design

3.1 Mechanical Characteristics of the Developed System

Our second objective was to design the force transmission system and make a proof-of-concept prototype pincer for the chosen type of kinematics. The essential DOF required for the instrument pincer tip during a suturing procedure is in two independent rotational axis movements: roll and yaw. While it is crucial to execute the full range rotations in required orientation, it is also important to maintain the position in the proposed configuration with a high stiffness and rigidity. The mechanical design challenge lies in developing an instrument in thin (5mm) cylindrical shape. Here we introduce two prototypes that can produce two independent and simultaneous orthogonal rotations amid the constraints imposed by practical usage in operating rooms.

Metallic Bellow Model. In order to transmit the rotational movement of the pincer tip (roll), while the body is in motion (yaw), a metallic bellow is used. This inner bellow tubing is actively bended by wedged sleeves and is completely independent from the outer rings which have chiseled slopes for making the curvature which are 90 deg = fold and 180 deg = tension. Such actuation is carried out by two cables (0.3mm dia. 5kg load multi-stranded steel cable) attached on the sides. A single cable (multi stranded stainless cable 0.75mm dia.) actuated pincer is affixed to the bellow joint. The cable is flexible yet robust to take the shape of the outer structure that controls the yaw direction of the end pincer. This pincer assembly rotates freely from the outer shell while maintaining its longitudinal position by a polymer bearing. The wedged sleeve links are formed that the instrument tip operates in either 0 or 90 degrees positions: The rigidity of the instrument is guarded and controlled by the cable tension on the side. Also, here it can be noted that the assembly configuration can be reversed to have the bellow either on the inside or outside.

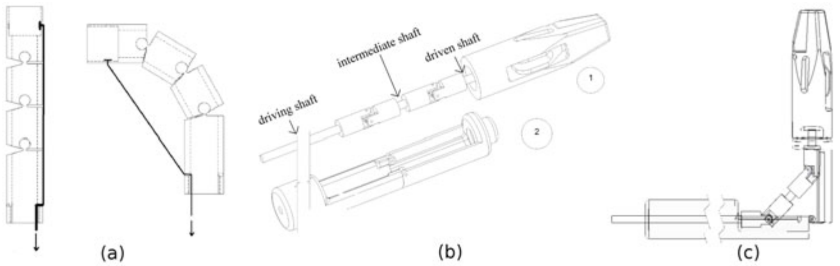

Fig. 5. (a) Metallic bellow model's wedged shell assembly with cable transmission for bending, (b) Universal joint and pincer assembly: (1) double universal joint and pincer assembly (2) shell unit, (c) Instrument in 90 degrees yaw position

Universal Joint Model. In this model, the bending in yaw direction is actuated by the linear translation of the outer shell (Fig. 5(b2)) with respect to the two universal joints and the pincer assembly (Fig. 5(b1)). Depending on the advancement of the shell unit that can bend maximum 90 degrees from its 0 degree straight position, the universal joint unit can transmit the rotation at the pincer tip. Due to the nature of the universal joint (gimbal adjoining unit fixes two rotating shafts), the rotary transmission experiences jerks and sinusoidal rotational velocity at the driven shaft: at 45 degrees off set of rotating axles, sinusoidal rotational velocity variance is about 40% at the driven shaft. The use of double universal joints minimizes this effect.

Fig. 6 shows shows the designed and manufactured prototypes. They are both 6mm -our primary objective was 5mm- in the diameter and use the same needle holder pincer tips and are fabricated in stainless steel.Current prototypes do not have the force/torque requirements for suturing and need to be improved for an animal experiment.

Fig. 6. (a) The two developed end-effectors, (b) Photograph of one of the developed prototypes

4 Conclusion and Future Work

The results of our evaluations suggest that the YR kinematics is the optimal kinematics for the end-effector. 2 proof of concept prototypes of such an end-effector were made introducing novel designs. The device needs a handle with an ergonomic design and a more robust force transmission system enabling the surgeon to suture different types of tissue. A new version of the device is under development.

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