Review Article

Endoscopic robotic suturing: The way forward

Hung Leng Kaan[1], Khek Yu Ho[2]

Departments of [1]General Surgery and [2]Medicine, National University Hospital, Singapore

Abstract Traditionally, suturing is performed in open surgery using a needle holder and forceps. The aim is to achieve accurate approximation of both edges of the wound and to tie a secure knot. With the development of laparoscopic surgery, traditional suturing methods have been adapted to meet the constraints of rigid laparoscopic instruments with limited degrees of freedom. The subsequent introduction of three-dimensional robotic suturing has since made intracorporeal suturing easier to learn, primarily because of its intuitiveness and the additional degree of freedom of the robotic wrists. With the increasing popularity of therapeutic endoscopic procedures for early gastrointestinal cancers, devices allowing for endoscopic suturing have since been developed. Nevertheless, these devices remain challenging to use as they require double-channel endoscopes and do not have the extra degree of freedom of robotic wrists. The introduction of robotics to the field of endoscopic suturing has proven to be promising. This review describes the development and adaptation of basic suturing techniques to various platforms, such as laparoscopic, robotic and endoscopic.

Keywords: Flexible endoscopy, robotics, suture techniques, therapeutic endoscopy

Address for correspondence: Prof. Khek-Yu Ho, Department of Medicine, National University of Singapore, 1E Kent Ridge Road, NUHS Tower Block Level 10, Singapore - 119228, Singapore.
E-mail: mdchoky@nus.edu.sg

INTRODUCTION

In open surgery, suturing is performed by using a needle holder on one arm to drive the needle through the tissue with a full thickness bite and forceps on the opposite arm to evert the edge of the wound. The eventual goals are, first, to achieve accurate and precise approximation of both edges of the wound to promote wound healing via primary intention and, second, to achieve a secure knot that does not slip, without applying excessive tension on the tissues.

The introduction of laparoscopic surgery has resulted in the development of modified suturing techniques. This is primarily to overcome the technical limitations associated with laparoscopic procedures, such as the limited degree of freedom of rigid laparoscopic instruments. Robotic suturing has further improved the feasibility and ease of learning intracorporeal suturing. The benefits of three-dimensional robotic suturing are its intuitiveness and additional degrees of freedom of the robotic wrists.[1]

Despite the minimally invasive nature of laparoscopic and robotic surgery, surgical incisions and scars are still part of these procedures. In the 1990s, Japanese doctors developed endoscopic surgery of the gastrointestinal tract as a minimally invasive method of removing early-stage carcinomas. The introduction of endoscopic submucosal dissection (ESD) allowed patients to be spared major surgeries and reduced the length of stay and resources required.

Nevertheless, a major complication of ESD is iatrogenic perforation.[2] Because of this inherent complication, it is

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paramount that endoscopists are provided with endoscopic suturing devices. This will allow endoscopists to suture iatrogenic perforations endoscopically, instead of relying on surgical intervention. As the field of endoscopic suturing has only been introduced recently, many of the current endoscopic suturing devices are still challenging to use.[3] The need to use a double-channel endoscope and the lack of extra degree of freedom of robotic wrists are the main problems of current devices.

SUTURING ON VARIOUS PLATFORMS

Laparoscopic suturing

Laparoscopic surgery has evolved to become the standard of care for a wide variety of surgical conditions. As a result, learning to suture intracorporeally using rigid laparoscopic instruments has become paramount in the training of a laparoscopic surgeon.

The traditional laparoscopic suturing technique involves the use of two laparoscopic needle drivers and a curved needle to perform intracorporeal suturing and knot tying.[4] This technique is challenging as it involves advanced laparoscopic skills to mount the needle on the needle driver, pass the needle between the two instruments, form loops, and tie secure knots.

One of the main drawbacks of laparoscopic suturing is its limited degree of freedom and two-dimensional vision. The pivoting effect and fulcrum further adds on to the difficulty of performing laparoscopic suturing. Bermas *et al.* showed that there is a steep learning curve in acquiring the skill of laparoscopic intracorporeal suturing. There was a statistically significant difference in the average intracorporeal knot-tying times by surgeon skill level – experienced versus less experienced versus surgical chief residents (97.3 vs. 237.2 vs. 265.3 s, $P < 0.01$).[4]

Robotic suturing

The benefits of increased degrees of freedom of the robotic wrists and three-dimensional vision have made robotic suturing easier and more intuitive to learn as compared with laparoscopic suturing. Robotic devices help to minimize the steep learning curve associated with laparoscopic suturing. This is especially useful when performing complex surgical procedures such as intracorporeal anastomosis. Marecik *et al.* showed that performing an intracorporeal anastomosis was considered difficult by 92% of the residents in the laparoscopic group versus 17% in the robotic group.[5]

Nevertheless, other studies have demonstrated that this benefit is primarily to the inexperienced surgeons and that the learning curve is relatively flat in experienced surgeons. Heemskerk *et al.* demonstrated that the benefit of robotic assistance is primarily in the group of inexperienced surgeons, hence explaining why robotic assistance for laparoscopic surgeons had not shown a clear benefit in various clinical studies.[6] Chandra *et al.* also showed that robotics helped to eliminate the early learning curve for surgical novices, which was present in learning laparoscopic suturing.

However, for expert surgeons, the learning curve is similar and the main benefit of robotics is the improved economy of motion, making it especially useful in pelvic surgeries with limited workspaces.[7]

In terms of ergonomics, several studies have also shown that surgeons experience less discomfort when performing a robotic procedure as compared to a laparoscopic procedure. A survey conducted by Stanford University of 1215 surgeons showed that 55.4% of physical symptoms experienced by surgeons were attributed to laparoscopic surgery, while only 8.3% was due to robotic surgery.[8] Elhage *et al.* showed that the level of self-reported discomfort amongst a group of urologists was highest for the laparoscopic approach ($P < 0.005$). With less discomfort experienced during the robotic procedure, the time taken to complete the surgery was also shorter (116 s for robotic approach vs. 221 s for laparoscopic approach vs. 55 s for open approach, $P < 0.005$).[9]

Endoscopic suturing

In the last decade, numerous advances have been made in the field of therapeutic endoscopy. One of the exciting developments was the introduction of endoscopic suturing devices. With these devices, endoscopists can now perform more extensive therapeutic procedures with confidence, as iatrogenic perforations or full thickness defects can be sutured closed endoscopically without any surgical intervention.

Endoscopic string clip suturing method

A Japanese group has developed a suturing method using string and clips for a single-channel endoscope.[10] They have performed a prospective pilot study of 10 patients who underwent ESD for a duodenal tumor. Perforation occurred in one patient and was successfully closed using this method. They demonstrated that the length of stay was significantly shorter compared with the no-suture group ($P = 0.038$).

Apollo Endosurgery OverStitch

The introduction of OverStitch has allowed endoscopists to perform a wide variety of procedures, including suturing of perforations and full thickness defects that may result from ESD, peroral endoscopic myotomy, and Natural Orifice Transluminal Endoscopic Surgery (NOTES).

OverStitch can also be used to fix stents and perform primary sleeve gastroplasty.[11] It is currently the only Food and Drug Administration-approved endoscopic suturing device that is available in the commercial market.

Li *et al*. demonstrated successful anastomotic suturing using OverStitch in the treatment of gastroesophageal reflux disease.[12] The group believed that the main advantage of the OverStitch suturing system was its ability to provide robust tissue approximation, equal to that of open surgery. A group in Germany also showed that the OverStitch endoscopic suturing system can be used to close an anastomotic leak after esophagogastrostomy, with immediate technical and clinical success.[13]

An international case series of patients undergoing endoscopic suturing for bleeding peptic ulcer disease, using OverStitch, was reported by a collaborative group from America and Hong Kong.[14] Their results showed that endoscopic suturing is especially useful in the group of patients who had failed prior endoscopic hemostatic attempts. Technical success was achieved in 100% of the cases. The rate of immediate hemostasis was 100% and the rate of early rebleeding was 0%. Endoscopic suturing may therefore be considered as rescue endoscopic therapy for patients who continue to bleed despite conventional endoscopic hemostatic methods.

Nevertheless, OverStitch is limited by the fact that it requires the use of a double-channel endoscope. This restricts the depth of insertion of the endoscope and its overall flexibility.[11] As such, suturing in deep locations such as the duodenum and right colon is extremely challenging.

Endoscopic suturing device using a computer-controlled master and slave robot

The Master and Slave TransEndoluminal Robot (MASTER) (Endomaster Pte. Ltd., Singapore) is a robotic endoscopic platform that has been clinically validated for ESD of early gastric neoplasia [Figure 1].[15] The main benefit of this system is its multiple degrees of freedom of both robotic wrists. It is able to perform both intraluminal and transluminal endoscopic procedures,[16,17] with an operation time comparable to that required using conventional methods.[18] Animal trials have also been conducted to demonstrate its potential in transluminal gastric full thickness resection and liver wedge resection.[19,20]

The use of this robot for endoscopic suturing is superior as it allows the operator to recreate manual human wrist movements that are essential for effective surgical suturing and knot tying. It also allows the user to concentrate on the procedure at hand instead of being involved in tedious repetitive manual tasks required in endoscopic suturing.[21] With this benefit in mind, we developed a novel suturing device using this MASTER system [Figure 2]. There are two main concepts in our novel suturing device for flexible endoscopy. First, it is intuitive and easy to use. Second, we deploy two robotic arms to allow for triangulation while performing knot tying.

We conducted an animal study using the novel endoscopic robotic device on an anaesthetized live pig. For this study, we performed an ESD in the pig's colon using the endoscopic suturing device and an external computer-controlled master and slave robot.

A double-channel scope was inserted into the rectum. The computer-controlled robotic arms were then inserted into the working channels of the colonoscope and controlled remotely via a master console. The left arm of the robot is a tissue grasper and the right arm of the robot is a needle drive. Both arms of the robot can be rotated 360°.

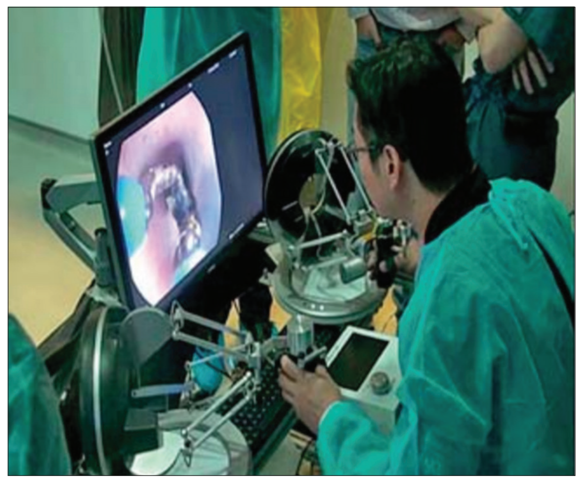

Figure 1: Using the MASTER endoscopic platform to perform endoscopic submucosal dissection (ESD)

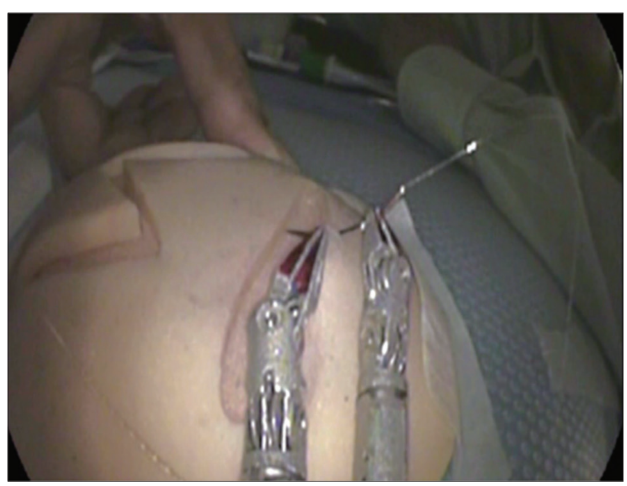

Figure 2: Endoscopic robotic suturing in a dry setting using a master and slave transluminal endoscopic robot

Table 1: Advantages and disadvantages of suturing using various platforms

Suturing platform	Advantages	Disadvantages
Laparoscopic suturing	Suturing equipment is light, portable, and readily available	Steep learning curve Rigid laparoscopic instruments without degree of freedom of robotic arms Two-dimensional vision
Robotic suturing	Additional degree of freedom of robotic arms Three-dimensional vision Improved economy of motion, especially useful in pelvic surgeries with limited workspaces More ergonomic with less discomfort experienced as compared to laparoscopic suturing More intuitive for surgeons to learn intracorporeal suturing	Requires an additional robotic console for operator to control
Endoscopic suturing	Suturing equipment is light, portable, and readily available	Require double channel endoscope Restricts depth of insertion of endoscope Overall flexibility limited
Endoscopic robotic suturing	Additional degree of freedom of robotic arms Three-dimensional vision	Requires an additional robotic console for operator to control

First, we performed a submucosal injection to lift up the lesion. Next, we performed an incision in the tissue. After loading the needle into the needle driver, a figure of eight sutures was then performed. Knots were tied by passing the needle between suture loops formed by the robotic arms.

Through the pilot animal study, we demonstrated that our novel endoscopic robotic device can be used to suture perforations that result from ESD, without the need for additional surgical intervention.

CONCLUSION

Despite vast advances in surgical technology, proper suturing technique remains the cornerstone of every surgical procedure performed on any platform. Acquiring laparoscopic suturing skills requires the surgeon to overcome a steep learning curve. The introduction of robotic suturing has made it easier and more intuitive for the surgeon to suture intracorporeally. With the additional degree of freedom of the robotic arms, adapting robotic technology to endoscopic suturing would allow for even more endoscopic therapeutic procedures to be performed [Table 1]. The field of endoscopic robotic suturing is developing, and with future innovations, endoscopic full-thickness resection sites and natural orifices used in NOTES can potentially be closed without surgical intervention.

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Conflicts of interest

Khek Yu Ho is the cofounder of EndoMaster Pte. Ltd., Singapore.

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