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Development and Feasibility of a Robotic Laparoscopic Clipping Tool for Wound Closure and Anastomosis

This paper reports the design, development, and initial evaluation of a robotic laparoscopic clipping tool for single manipulator wound closure and anastomosis (tubular reconnection). The tool deploys biodegradable clips and clasps with the goal of (i) integrating grasping and suturing into a single device for single hand or manipulator use, (ii) applying the equivalent of interrupted sutures without the need of managing suture thread, and (iii) allowing for full six degrees-of-freedom (DOFs) laparoscopic control when mounted on a robot arm. The specifications, workflow, and detailed design of the robotic laparoscopic tool and injection molded bio-absorbable T shaped clip and locking clasp are reported. The clipping tool integrates forceps to grab and stabilize tissue and a clip and clasp applicator to approximate and fixate the tissue. A curved needle is advanced on a circular needle path and picks up and drags clips through tissue. The clip is then tightened through the tissue and a clasp is clamped around the clip, before the clip is released from the needle. Results of several bench test runs of the tool show: (a) repeatable circular needle drive, (b) successful pick-up and deployment of clips, (c) successful shear of the clip to release the clip from the needle, and (d) closure of clasp on clip with an average of 2.0 N holding force. These data indicate that the robotic laparoscopic clipping tool could be used for laparoscopic wound closure and anastomosis.

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1 Introduction

Suturing is an essential element of surgical reconstruction performed more than a million times each year [1]. For centuries, the design of surgical tools and suture for open surgery has remained relatively unchanged [2]. In minimally invasive surgery (MIS), however, the surgeon must use laparoscopic tools to apply sutures through a small incision. This keyhole approach limits the surgeon's working volume, dexterity, and tool control, which make suturing more difficult. Surgical tasks such as anastomosis (tubular reconnection) in gastrointestinal, urologic, and gynecologic MIS require a more laborious and complex learning curve, and significant complication rates remain [3–5].

In MIS, efficient and effective anastomosis is necessary for patient healing [6,7]. In procedures such as kidney transplants, procedure outcome is poorer for anastomoses longer than 29 min [8]. On average, manual laparoscopic anastomosis can last from 30 to 90 min depending on the tissue sutured [9–11]. Laparoscopic staplers, such as the Endo GIA (Medtronic, Minneapolis, MN), perform anastomosis significantly quicker than manual suturing, with improved leak rate and bursting strength [12]. However, the linear shape and bulky footprint result in an increased stricture in bowel [13], while the utility of circular staplers is limited to proximal fore and distal hindgut [14,15]. Two laparoscopic suturing devices, Endo StitchTM (Covidien, MA) and Endo360 (EndoEvolution, Raynham, MA) [16], enable surgeons to manually suture with simplified motion. Comparison of manual anastomosis to these suturing tools demonstrates both time and cost of suturing are improved [17]. Unfortunately, intersurgeon variations in technique, experience, and decision still directly impact the consistency and quality of anastomosis [18].

The next generation tool for laparoscopic anastomosis should combine the selectivity, dexterity, and accuracy of suturing while incorporating the simplification and consistency of a mechanical

stapler. Our team recently developed the smart tissue autonomous robot (STAR) for supervised autonomous anastomoses [19]. STAR was used to perform bowel anastomosis in a porcine animal model, with more consistency, precision, and improved outcome compared to manual techniques [20]. The goal of this work is to combine the precision and repeatability of STAR with a laparoscopic single clip applicator to perform anastomosis that has consistency of staples, but the adaptability of sutures.

This paper reports the design, development, and initial evaluation of a robotic laparoscopic clipping tool for single manipulator wound closure and anastomosis. The tool deploys biodegradable clips and clasps with the goal of (i) integrating grasping and suturing into a single device for single hand or manipulator use, (ii) applying interrupted sutures without the need of managing suture thread, and (iii) allowing for full six degrees-of-freedom (DOFs) laparoscopic control when mounted on a robot arm. This paper is organized as follows: Section 2 reviews the requirements for performing one-handed anastomosis without tying knots, Sec. 3 describes the detailed design and workflow, Sec. 4 reviews the initial testing results, and Sec. 5 discusses and summarizes the results.

2 Requirements for the Clipping Tool

The laparoscopic clipping tool is a hybrid technology that combines the benefits of stapling and suturing techniques. The clipping mechanism enables approximation of tissue, i.e., bringing tissue together, before clipping, which is not possible for a stapler. A stapler also has a preset number and density of staples and cannot be adjusted to the need of the particular wound closure or anastomosis. By deploying individual clips and clasps, the clipping tool approximates target tissue with the same adaptability as interrupted suturing, but eliminates the time attributed to suture management. Additionally, clips are clasped with consistent force along the tissue edge, which may reduce the risk of dehiscence as observed with stapling technology. Table 1 summarizes the

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mechanical, operational, holding force, material, and size requirements for performing one-handed anastomosis without the need for tying knots. These requirements were developed after detailed discussions with experienced surgeons.

3 Clipping Tool Design

3.1 Overall Design and Surgical Workflow. A prototype clipping tool capable of anastomosis was designed and built. The laparoscopic clipping tool (Fig. 1) is cable driven and mounts to a five-axis motor stage, attached to a light weight robot (LWR) (LWR 4+, KUKA, Augsburg, Germany) manipulator. The clipping tool contains two ± 90 deg articulation joints for wristed dexterity in positioning the end effector. The tool also contains forceps jaws, to independently grasp and maneuver tissue, while a circular needle advances through target tissue. Injection molded bio-absorbable clips are attached to the needle with a loop. The clip is sheared from the needle once a clasp is tightened around the clip. Clip and clasp cartridges allow application of eight clips during anastomosis. A quick connect interface facilitates sterilization, and easy removal from an independently draped robotic positioning system.

Figure 2 illustrates the clinical work flow to apply a clip and clasp for side to side anastomosis. First, tissue is targeted and grasped between the forceps (Fig. 2(a)). Once secure, the needle is advanced just beyond the tissue surface, and the forceps are returned to the open state (Fig. 2(b)). After repositioning the end effector, a second layer of tissue can be grasped, and the needle with clip advanced through the tissue. When the T-shaped clip foot engages the second tissue (Fig. 2(c)), force is applied to both tissues as the needle advance and forceps axes synchronize to pull grasped tissue to the top of the clipping tool (Fig. 2(d)). Once oriented, a clasp is applied to the clip securing the tissues (Fig. 2(e)), while simultaneously shearing the clip from the needle.

3.2 Clip and Clasp Design. The clipping tool deploys bio-absorbable clips with 0.28 mm diameter, comparable to size 2-0 sutures by a rotating needle, see Fig. 3. The clip is attached to the needle with a loop. The clip is pulled through the tissue until the T-shaped end is pressed against the side of the tissue. The clip is then tightened through the tissue and a clasp is clamped around

Fig. 1 Rendering (top) and picture (bottom) of the prototype of a novel laparoscopic clipping tool to perform anastomosis during robotic MIS, consisting of a motor pack, laparoscopic shaft, and clipping tool head. Included are two ± 90 deg pitch and yaw articulation joints. The clipping tool is mounted to an LWR arm.

the clip, similarly to the commercially available LAPRA-TY (Ethicon Endo-Surgery, Somerville, NJ). Clips and clasps were injection molded using bio-absorbable poly(lactide-co-glycolide) (PLGA) material (PLG8218, MTD Micromolding, Charlton, MA), to avoid leaving permanent foreign materials in the body.

The latch of the clasp was designed to achieve a holding force of over 1 N so that tissue can be approximated without creating avascular regions during the healing process [21]. The holding force of the clasp was simulated by finite element analysis (FEA) using FEA software (NASTRAN), see Fig. 4. A first multistep, non-linear analysis using tetrahedral elements and generalized surface contact was used to generate a force versus displacement curve for the clip/clasp indentation. The clip stem was modeled with double symmetry and the “clasp” with planar symmetry as shown in the right panel of Fig. 4. The clasp was moved downward under enforced deflection and reaction loads were extracted from each

Table 1 Detailed design specifications for the robotic clipping tool

Category	Requirement	Value	Description and rationale
Mechanical	DOFs	2DOF (pitch plus yaw) for tool 6DOF overall	To achieve full position and pose control under laparoscopic constraints, clipping tool is required to have 2DOF and 6DOF overall together with robot arm
Mechanical	Work space	5 cm ³	The majority of anastomoses can be performed in a 5 × 5 × 5 cm ³ area
Mechanical	Angles	90° for both pitch and yaw	Wristed tool with full 90 deg range for both pitch and yaw
Mechanical	Connection	modular <1 min	Quick connect for modular and replaceable attachment of tool by a technician in under 1 min
Operation	Mode of operation	One manipulator ability to grab both sides bold tissue until healed	Single manipulator design that can grab and approximate two separate parts of tissues and provide holding force until wounds is healed
Forces	Holding forces for clip	>1 N	1 N is minimum holding force to achieve wound healing without separation
Material	Biodegradation	>2 weeks	2 weeks is minimum time clips need to provide holding force wound is sufficiently healed
Size	Tool and clip size	Tool shaft diameter 10 mm clip size 2-0	The tool shaft diameter for this prototype should not be larger than 10 mm and the clip should not be larger than standard 2-0 sutures

Fig. 2 Surgical workflow for applying a clip and clasp to two layers of tissue with the prototype clipping tool

step until an ideal claspings force of 4.02 N was determined (Table 2).

A second multistep, nonlinear analysis using tetrahedral elements and generalized surface contact was performed to determine if the clasp geometry could support the claspings force. This

analysis had two cases, which were run simultaneously: clasp closure, and downward translation of the clip. The result shown in the left panel of Fig. 4 illustrates when the clasp response matched the clasp indentation under a load of 4.02 N. The analysis was constrained along the bottom edge to enable local rotation, and stabilized in the lateral direction at a neutral point. Loads were applied via enforced displacement, first along the top of the clasp, and second on the clip downward. From the FEA, a pinch force of 4.02 N provided by the latched clasp generates a clip deflection of

Fig. 3 Microscope picture (scale is 1 mm) of a custom molded size 2-0 polymer T-shaped clip and clasp

Table 2 Holding force results of six consecutive biodegradable clasp latches

Experiments clasp material: PLG8218 clips material: polypropylene		
Sample	Clasping successful	Strip force N (peak)
6	Yes	1.9
5	Yes	1.9
4	Yes	2.23
3	Yes	1.61
2	Yes	1.97
1	Yes	2.38
Mean		2.00
Stdev		0.27

Fig. 4 Screenshots of FEA analysis of clasp and clip interaction, used to design the latch

Fig. 5 Computer aided design picture of clipping tool head with components of forceps mechanism

0.48 mm. For a static model with constant pressure, the static friction of the clip is equivalent to the holding force of the clasp. Assuming a friction coefficient of 0.1, the static friction was calculated to be 1.26 N.

The full clasp mechanism is described in Sec. 3.3. The tool incorporates a clip cartridge design that sits between the lower forceps jaw and the tool body. The location of the cartridge aligns the clip's loop with the needle path so that it is pulled from the cartridge during the needle advance. The clip cartridge is spring loaded so that a new clip is automatically advanced into the path of the needle. Each cartridge can dispense up to eight clips without the need for reloading.

3.3 Clipping Tool Head Design. The clipping tool head contains three cable actuations and a fourth mechanism: (a) cable actuated forceps jaws to grasp and hold tissue during the anastomosis, (b) cable actuated needle drive to advance the circular needle, (c) a wire actuated clip shear to separate the clip from the needle once a clasp is tightened around the clip, and (d) a clasp mechanism that is coupled to the forceps to attach a clasp to the clip.

Forceps mechanism: Figure 5 shows a computer-aided design picture of the clipping tool head and illustrates the components of the forceps mechanism. The forceps is biased closed and opened along a rotational path by pulling on a cable connected to the forceps. The closing force is provided by a compression spring connected to the forceps (through a second cable). The closing force is tuned by adjusting the position of a stopper. The spring loaded closure design limits the forceps' closing force and mitigates the potential of tissue damage.

Needle advance mechanism: The needle advance consists of a rotating ratchet mechanism, where a pull wire actuates a needle advance arm in a rotational track (Fig. 6). The needle advance arm engages a notch in the needle every 10 deg, via four welded on advance springs. The return of the needle advance is performed by a set of leaf springs. Anti-back drive springs engage with notches placed every 5 deg on the outside of the needle to prevent the needle from sliding backward. This ratchet mechanism advances the needle 10 deg per wire pull along a circular needle path. The needle hook is used to pick up the clip from the cartridge and drag it through the bottom part of the needle track and deploy it in the tissue.

Clasping mechanism: The clasping mechanism (see Fig. 7) is activated by the opening of the forceps, which presses a lever against the housing of the clipping tool head. This motion simultaneously actuates a cam pushing against the latch of the clasp until the clasp is closed around a clip. After shearing the loop of the clip, the forceps are then slightly opened again to release the clip.

Shear mechanism: To release the clip from the clipping tool and needle, a shear blade is used to sever the loop on the clip. The shearing of the loop is achieved by a cable actuated shear blade in a linear track inside the clipping tool head (see Fig. 6). Similarly to the forceps mechanism, the shear closing force is provided by a compression spring connected to the shear blade with a cable.

Fig. 6 Computer aided design picture of clipping tool head with components for needle advance drive. Needle is shown in an exploded view.

Fig. 7 Panel A: Computer aided design picture of clipping head with clasping mechanism. Retracting the forceps actuates a lever that initiates the closing of a Clasp via a Cam. Panel B: Microscope picture of open Clasp inside mechanism. Panel C: Clasp inside mechanism after latch is closed.

3.4 Motor Pack and Actuation. A five-axis motor stage was designed and built that articulates and actuates the clipping tool and mounts to an LWR manipulator (see Fig. 1). The first two rotary axes drive ± 90 deg articulation joints for wristed dexterity in positioning the clipping tool. The third rotary axis is responsible for activating the shearing of the clip. The fourth axis actuates the needle advance and the fifth axis the forceps jaws. Figure 8 presents the schematic of the cable-driven actuation. Control of each axis is achieved through EPOS2 controllers (Maxon Motors, Sachseln, Switzerland), which orient DC Brush Motors (Maxon Motors) through controller area network communication. An interface with individual spring-loaded push-pins couples the rotary motion from the motors to the tool. A single large screw facilitates quick connection of the tool to the motor pack for easy attachment and removal (Fig. 1). The shaft diameter of the laparoscopic tool is 10 mm.

4 Testing Results

Mechanical tests: After careful assembly and tuning, the functionality of each mechanism of the clipping tool was confirmed. The clipping tool articulation was successfully tested with the pitch and yaw joints over the full ± 90 deg range. The forcep's opening and closing worked well. The needle drive of the clipping

Fig. 8 Schematic of cable actuation of the clipping tool with five control cables

Fig. 9 Microscope picture of an example of a successful latching of a clasp on a clip

tool successfully ran for 700 consecutive rotations of the needle, before the drive springs wore out. Clips were successfully picked up with the needle on 30 consecutive runs and the experiment was stopped. Basic functionality of the clip shear was also confirmed by consecutive shearing of three clip loops before the shear blade wore out. The wear on the drive springs and on the shear blade prevented more extensive testing with this first prototype.

Clipping tests: To measure the maximum holding force, a bio-absorbable PLGA clasp was closed onto a clip. The foot of the clip was fixed to a vise, while the clasp was secured to a force sensor. The force sensor was pulled axially until the clasp slipped off the clip. The instantaneous force when the clasp disengaged from the clip was recorded as the maximum holding force. The test was then repeated for a total of six clips and clasps. All six clasps successfully latched onto clips with an average of 2.0 ± 0.27 N holding forces, which exceeded the FEA results and is above the requirement to approximate tissue for wound closure and anastomosis. Figure 9 shows an example of a successfully latched clasp onto a clip.

After successful holding force tests, the clipping tool was used to perform side-to-side anastomosis, see Fig. 2. An expert operator was asked to use the tool to apply three consecutive clips into phantom small bowel tissue (Syndaver Tampa, FL). The operator successfully actuated the forceps jaws to approximate the

synthetic tissue, while simultaneously operating the needle advance to plant all three clips across two layers of synthetic tissue. Each clip was secured in place by activating the clasp and shear mechanisms to apply a PLGA clasp to each clip.

5 Discussion and Conclusion

This paper reported the design, development, and initial evaluation of a robotic laparoscopic clipping tool for single manipulator wound closure and anastomosis. The tool eliminates the need for knot tying and suture management while maintaining the advantages and workflow of a mechanical suturing technique. The laparoscopic clipping tool is a technological step toward fast and simple single-hand manipulator anastomosis with applications as a new hand tool, tele-operated robot assisted surgery tool, or tool for autonomous robotic anastomosis.

Results of several test runs of the tool show: (a) repeatable successful circular needle drive, (b) successful pick-up and deployment of clips, (c) successful shear of the clip to release the clip from the needle, and (d) clasping of clip on clasp with an average of 2.0 N holding force, which exceeds the FEA results and is above the requirement to approximate tissue for wound closure and anastomosis. The data indicate the robotic laparoscopic clipping tool could be used for laparoscopic wound closure and anastomosis.

In the future, we propose to develop a version of the clipping tool that is prototyped from a more wear resistant metal and machined with more reliable techniques. A new drive mechanism with thicker drive springs will be prototyped from a more robust material to reduce mechanical wear. The larger surface area will also provide a better weld, which will improve the longevity of each leaf spring. Additionally, the shear blade will be prototyped from ground surgical steel. The resulting blade will perform similarly to a scalpel. Finally, the tool will be fully integrated into a robotic platform, actuated robotically, and designed for sterilization to perform preclinical testing. The new clipping tool will be trialed in a usability and comparison study against the standard laparoscopic technique with interrupted sutures. Expert surgeons will be instructed to perform anastomosis of the small bowel, and samples will be compared for timing, clip or suture spacing, and resulting burst pressure.

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Nomenclature

DOF = degree-of-freedom
 FEA = finite element analysis
 LWR = light weight robot
 MIS = minimally invasive surgery
 PLGA = poly(lactide-co-glycolide)
 STAR = smart tissue autonomous robot

References

- [1] Weiser, T. G., Regenbogen, S. E., Thompson, K. D., Haynes, A. B., Lipsitz, S. R., Berry, W. R., and Gawande, A. A., 2008, "An Estimation of the Global Volume of Surgery: A Modelling Strategy Based on Available Data," *Lancet*, **372**(9633), pp. 139–144.
- [2] Kirkup, J. R., 1981, "The History and Evolution of Surgical Instruments—I: Introduction," *Ann. R. Coll. Surg. Engl.*, **63**(4), pp. 279–285.
- [3] Chapron, C., Querleu, D., Bruhat, M. A., Madelenat, P., Fernandez, H., Pierre, F., and Dubuisson, J. B., 1998, "Surgical Complications of Diagnostic and Operative Gynaecological Laparoscopy: A Series of 29,966 Cases," *Hum. Reprod.*, **13**(4), pp. 867–872.
- [4] Fullum, T. M., Ladapo, J. A., Borah, B. J., and Gunnarsson, C. L., 2010, "Comparison of the Clinical and Economic Outcomes Between Open and Minimally Invasive Appendectomy and Colectomy: Evidence From a Large Commercial Payer Database," *Surg. Endoscopy*, **24**(4), pp. 845–853.
- [5] Noel, J. K., Fahrbach, K., Estok, R., Cella, C., Frame, D., Linz, H., Cima, R. R., Dozois, E. J., and Senagore, A. J., 2007, "Minimally Invasive Colorectal Resection Outcomes: Short-Term Comparison With Open Procedures," *J. Am. Coll. Surg.*, **204**(2), pp. 291–307.
- [6] Lau, W. Y., Leung, K. L., Kwong, K. H., Davey, I. C., Robertson, C., Dawson, J. J., Chung, S. C., and Li, A. K., 1996, "A Randomized Study Comparing Laparoscopic Versus Open Repair of Perforated Peptic Ulcer Using Suture or Sutureless Technique," *Ann. Surg.*, **224**(2), pp. 131–138.
- [7] Neo, E. L., Patkin, M., and Watson, D. I., 2004, "Suturing Efficiency During Hiatal Repair for Laparoscopic Fundoplication," *ANZ J. Surg.*, **74**(1–2), pp. 13–17.
- [8] Marzouk, K., Lawen, J., Alwayn, I., and Kiberd, B. A., 2013, "The Impact of Vascular Anastomosis Time on Early Kidney Transplant Outcomes," *Transplant. Res.*, **2**(1), p. 8.
- [9] Hollands, C. M., Dixey, L. N., and Torma, M. J., 2001, "Technical Assessment of Porcine Enterostomy Performed With ZEUS Robotic Technology," *J. Pediatr. Surg.*, **36**(8), pp. 1231–1233.
- [10] Dion, Y. M., Hartung, O., Gracia, C., and Doillon, C., 1999, "Experimental Laparoscopic Aortobifemoral Bypass With End-to-Side Aortic Anastomosis," *Surg. Laparoscopic Endoscopy*, **9**(1), pp. 35–38.
- [11] Hoznek, A., Salomon, L., Rabii, R., Ben Salama, M. R., Cicco, A., Antiphon, P., and Abbou, C. C., 2000, "Vesicourethral Anastomosis During Laparoscopic Radical Prostatectomy: The Running Suture Method," *J. Endourol.*, **14**(9), pp. 749–753.
- [12] Seo, S. H., Kim, K. H., Kim, M. C., Choi, H. J., and Jung, G. J., 2012, "Comparative Study of Hand-Sutured Versus Circular Stapled Anastomosis for Gastrojejunostomy in Laparoscopy Assisted Distal Gastrectomy," *J. Gastric Cancer*, **12**(2), pp. 120–125.
- [13] Gonzalez, R., Lin, E., Venkatesh, K. R., Bowers, S. P., and Smith, C. D., 2003, "Gastrojejunostomy During Laparoscopic Gastric Bypass: Analysis of 3 Techniques," *Arch. Surg.*, **138**(2), pp. 181–184.
- [14] Nguyen, N. T., and Wolfe, B. M., 2000, "Hypopharyngeal Perforation During Laparoscopic Roux-En-Y Gastric Bypass," *Obes. Surg.*, **10**(1), pp. 64–67.
- [15] de la Torre, R. A., and Scott, J. S., 1999, "Laparoscopic Roux-En-Y Gastric Bypass: A Totally Intra-Abdominal Approach—Technique and Preliminary Report," *Obes. Surg.*, **9**(5), pp. 492–498.
- [16] Adams, J. B., Schulam, P. G., Moore, R. G., Partin, A. W., and Kavoussi, L. R., 1995, "New Laparoscopic Suturing Device: Initial Clinical Experience," *Urology*, **46**(2), pp. 242–245.
- [17] Hashemi, L., Hart, S., Craig, S., Geraci, D., and Shatskih, E., 2011, "Effect of an Automated Suturing Device on Cost and Operating Room Time in Laparoscopic Total Abdominal Hysterectomies," *J. Minimally Invasive Gynecol.*, **18**(6), pp. S96–S97.
- [18] Harold, K. L., Matthews, B. D., Backus, C. L., Pratt, B. L., and Heniford, B. T., 2002, "Prospective Randomized Evaluation of Surgical Resident Proficiency With Laparoscopic Suturing After Course Instruction," *Surg. Endoscopy*, **16**(12), pp. 1729–1731.
- [19] Leonard, S., Wu, K. L., Kim, Y., Krieger, A., and Kim, P. C. W., 2014, "Smart Tissue Anastomosis Robot (STAR): A Vision-Guided Robotics System for Laparoscopic Suturing," *IEEE Trans. Biomed. Eng.*, **61**(4), pp. 1305–1317.
- [20] Shademan, A., Decker, R. S., Opfermann, J. D., Leonard, S., Krieger, A., and Kim, P. C., 2016, "Supervised Autonomous Robotic Soft Tissue Surgery," *Sci. Transl. Med.*, **8**(337), p. 337ra64.
- [21] Waninger, J., Kauffmann, G., Shah, I., and Farthmann, E., 1992, "Influence of the Distance Between Interrupted Sutures and the Tension of Sutures on the Healing of Experimental Colonic Anastomosis," *Am. J. Surg.*, **163**(3), pp. 319–323.