Medical Hypotheses 124 (2019) 76–83

Contents lists available at ScienceDirect

Medical Hypotheses

journal homepage: www.elsevier.com/locate/mehy

A minimally invasive robotic surgery approach to perform totally endoscopic coronary artery bypass on beating hearts

Alireza Alamdar[a], Shahrzad Hanife[a], Farzam Farahmand[a,b,*], Saeed Behzadipour[a], Alireza Mirbagheri[c,b]

[a] Department of Mechanical Engineering, Sharif University of Technology, Tehran, Iran
[b] Research Center for Biomedical Technologies and Robotics (RCBTR), Tehran University of Medical Sciences, Tehran, Iran
[c] Department of Medical Physics & Biomedical Engineering, School of Medicine, Iran

ABSTRACT

The currently available robotic systems rely on rigid heart stabilizers to perform totally endoscopic coronary artery bypass (TECAB) surgery on beating hearts. Although such stabilizers facilitate the anastomosis procedure by immobilizing the heart and holding the surgery site steady, they can cause damage to the heart tissue and rupture of the capillary vessels, due to applying relatively large pressures on the epicardium. In this paper, we propose an advanced robotic approach to perform TECAB on a beating heart with minimal invasiveness. The idea comes from the fact that the main pulsations of the heart occur as excursions in normal direction, i.e., perpendicular to the heart surface. We devise a 1-DOF flexible heart stabilizer which eliminates the lateral movements of the heart, and a 1-DOF compensator mechanism which follows the heart trajectory in the normal direction, thus canceling the relative motion between the surgical tool and the heart surface. In fact, we bring a compromise between two radical approaches of operating on a completely immobilized beating heart with no heart motion compensation, and operating on a freely beating heart with full compensation of heart motion, considering the invasiveness of the first and the technical challenges of the second approach. We propose operating on a partially stabilized beating heart with unidirectional compensation of the heart motion; the flexible stabilizer would exert much less holding force to the heart tissue and the robotic system with unidirectional compensator would be technically feasible. In the proposed approach, a motion sensor mounted on the stabilizer measures the heart excursion data and sends it into a control unit. A predictive controller uses this data to generate an automated trajectory. The slave robots follow this trajectory, which is superimposed on the surgeon's tele-operation commands received from a master console. Finally, the tool-activation units in the slave robots actuate the articulated laparoscopic tools to perform the anastomosis procedure. The evaluation of the hypothesis showed that our solution for the robotic TECAB on beating heart is both practical and cost effective. We showed in an in-vivo study that the flexible stabilizer can effectively restrict the heart lateral movements, while allowing for its normal excursion. We found readily available linear motors which could afford the high forces, speeds and accelerations required for following the heart trajectory. Finally, we showed that the tool-activation unit is capable of providing the maneuverability and workspace required for the most challenging task of CABG procedure, i.e., anastomosis suturing.

Introduction

Cardiovascular diseases have been the leading cause of death for many years and are expected to remain so. Among them, coronary artery diseases are the most prevalent and account for one in every seven death recorded in the USA [1]. They happen by plague buildup inside coronary arteries, which narrows the vessels and reduces the blood flow and oxygen supply to the heart tissue, causing cell death, Angina or even cardiac arrest. Treatment methods for coronary artery diseases include changing lifestyle, medication, angioplasty and Coronary Artery Bypass Graft (CABG) surgery [2].

During CABG surgery, the physician harvests an artery (graft) from elsewhere in the patient body (usually the saphenous vein from the leg or the left internal thoracic artery) and bypasses the blocked coronary artery. By doing so, the normal blood flow returns and the risk of heart attack subsides [3]. Surgeons perform CABG in a variety of techniques including open, minimally invasive, and totally endoscopic surgery.

Conventional open heart surgery is the most common CABG procedure. The surgeons make a large incision alongside the sternum and crack it open to fully access the heart. In on-pump technique, the heart is stopped and a heart-lung machine is used to circulate blood inside the body [3]. Although a still heart makes the operation much easier for the surgeon, such Cardio-Pulmonary Bypass (CPB) increases the risk of secondary complications such as emboli [4], renal failure, cerebrovascular accidents, and systemic inflammation [5]. The alternative off-pump technique eliminates the risks of CPB by enabling operation to be performed on a beating heart [3]. In this technique, an stabilization device immobilizes the heart and holds the anastomosis site steady, while the heart continues to beat, removing the need for CPB [3].

Both on-pump and off-pump conventional open heart CABG

* Corresponding author at: Mechanical Engineering Department, Sharif University of Technology, Azadi Avenue, Tehran, Iran.
E-mail addresses: farahmand@sharif.edu (F. Farahmand), behzadipour@sharif.edu (S. Behzadipour), a-mirbagheri@tums.ac.ir (A. Mirbagheri).

https://doi.org/10.1016/j.mehy.2019.02.005
Received 22 September 2018; Accepted 1 February 2019

procedures are highly invasive surgical techniques since they require cutting the sternum and opening the chest. An alternative solution is to make a number of small incisions between the ribs and perform the surgery using endoscopic instruments. Obviously, with such minimally invasive CABG technique, the traumatic impact of the operation would reduce dramatically and the patients experience less blood loss and pain, recover more quickly, and suffer fewer complications [3,6–10].

A variety of minimally invasive CABG techniques have been utilized in surgical practice. The two most common procedures are Minimally Invasive Direct Coronary Artery Bypass (MIDCAB) and Minimally Invasive CABG (MICS CABG). The MIDCAB procedure involves small thoracotomy over the fourth or fifth left intercostal space and off-pump harvesting and grafting of the left internal mammary artery (LIMA) to the left anterior descending artery (LAD) [9,11–15]. Based on clinical reports [12,16], the conventional MIDCAB is faced with a number of limitations, including poor maneuverability, inadequate access to the LIMA, and inability of revascularization of the arteries other than LAD. The more recent MICS CABG procedure resolves some of these problems, by suggesting a more lateral thoracotomy [10–12]. However, insufficiencies such as limited access, poor visualization, slow learning curve, and the need for complex exposure, harvesting and anastomosis maneuvers remain unsettled [10,15].

The robotic technology can help overcoming the difficulties associated with MIDCAB and MICS CABG by providing great control, excellent view, and a comfortable posture for the surgeon. During the past two decades, a variety of surgical robotic systems have been developed, including Da Vinci from Intuitive Surgical [7,17], Raven from University of Washington, Seattle [7], MiroSurge from DLR, Germany [7,18], SPORTS from Titan Medical, Canada [19,20], TELELAP Alf-X from SOFAR, Italy [20], Senhance™ from Transenterix [21] and so on. Among them, Da Vinci, is the only FDA-approved surgical robot for cardiac surgery [15,19]. In robotic minimally invasive CABG, an endoscopic camera provides a high quality detailed view of the surgery site, which helps performing the exposing, harvesting and grafting procedures more conveniently and accurately. The highly articulated end-effectors enhance the surgeon maneuvers, and the sophisticated control system enables hand tremor filtering and three-dimensional motion magnification, both facilitating the delicate high precision motions required for coronary artery anastomosis. Finally, the thoracotomy incision reduces to 4 to 5 cm and the rib opening is kept minimized [3,8,10–12,15,22,23]. The robotic surgical systems can also facilitate the Totally Endoscopic Coronary Artery Bypass (TECAB) surgery which minimizes the invasiveness even more and also reduces the operation time by eliminating the need for intercostal incision [6,23–26]. Clinical studies, comparing the outcomes of the robotic cardiac surgery and conventional mid-sternotomy CABG techniques, have often reported statistically significant results in favor of the robotic approach, in terms of reducing the mean duration of ventilation, ICU stay, and hospital stay [11,14,27–32].

The minimally invasive CABG procedures might be performed on beating hearts, by means of minimally invasive stabilizer, which is located on the target area via an additional intercostal incision, or a recently developed endoscopic heart stabilizer [6]. The surgery, however, would be complicated, even in case of using surgical robots, due to the residual motions of the heart [33–36]. More importantly, the heart stabilizer provides mechanical stabilization by applying relatively large pressures on the epicardium, as well as a strong vacuum attachment to the heart surface, that can by invasive. It has been reported that the forces applied by the stabilizers to immobilize the heart may cause damage to the heart tissue and rupture of the capillary vessels [18,19]. In particular, in spite of the generally acceptable results reported for Da Vinci in performing robotic minimally invasive cardiac procedures [6,24,25,37], there are concerns over its usage in stabilized beating heart operations due to the probable damage to the heart tissue [34,35].

In this paper, we propose an advanced robotic approach for beating heart TECAB, as the "ultimate goal of bypass surgery" [25]. The aim of this approach is to minimize the invasiveness of the current practice of robotic TECAB, by reducing the restricting effects of the stabilizers and allowing the heart surface to move freely along the normal direction during operation. We seek a solution that is both practical and cost effective. Our main concerns include minimum invasiveness, feasible implementation and affordability (for both patient and hospital).

Our conception

Robotic compensation of the heart motion is an alternative strategy to the stabilizer-based approach for beating heart TECAB surgery. The heart surface trajectory, captured by a motion sensor, is followed by the robotic arms that carry the surgical tools. Hence, there would be no relative motion between the tools and the heart surface [38–41], enabling the surgeon to operate on a practically still heart. The surgeon also enjoys a virtually stabilized view of the surgical site, provided by the endoscopic camera attached to the robotic arms [42].

In spite of its attractiveness from clinical point of view, performing robotic compensation of the heart motion has many technical challenges. Heart surface has a very complex motion, including three dimensional translations and rotations. To fully compensate the heart motion, we require a highly dynamic robotic system with high frequency motors and large bandwidth control in six degrees of freedom (DOF). Achieving such level of dynamic maneuverability is impractical with the currently available technology: it demands for a strong structure, complicated mechanisms and very powerful motors, making the system oversized and overweighed for heart surgery application.

In this paper, we propose a hybrid approach for performing robotic TECAB on beating heart, considering the reports that the main pulsations of heart occur as excursions in normal direction, i.e., perpendicular to the heart surface [43,44]. As illustrated schematically in Fig. 1, the proposed approach consists of a 1-DOF heart stabilizer, a slave robot, a master console and a control unit. The specially designed heart stabilizer allows the heart surface to move freely in the normal direction, while eliminating the side movements at the target area. Hence, it is sufficient to compensate the heart surface motion only in the normal direction. A motion sensor, mounted on the heart stabilizer, measures the heart excursion data in the dominant normal direction and sends into the control unit. A predictive controller [45] uses this data, as well as the trajectory data of previous heart beats, to generate an automated trajectory. The slave robot follows the automated trajectory from the predictive controller, which is superimposed on the surgeon's tele-operation commands received from the master console.

Slave robot

To provide the feel of an open surgery and completely follow the surgeon commands, we propose using 7-DOFs slave robots. The first three DOFs form the tool-orientation unit; they are used to move and rotate the surgical tool about the entry point. A 2-DOF "spherical mechanism" provides a remote center of motion (RCM), where the rotational axes of the mechanism and the tool axis coincide; this allows the robotic arm to pivot the tool around the incision point [46]. A 1-DOF linear mechanism inserts the tool into the body and controls its depth. This mechanism also acts as the compensator of the heart motion.

The remaining four DOFs of the slave robot form the tool-activation unit; they are used to drive the levers at the proximal end, i.e., handle, of the tool. A 2-DOF "Agile Eye" mechanism actuates the distal wrist joint of the tool, and another 2-DOF mechanism provides the roll and grasp motions [47]. The combination of these motions enables the slave robot to perform the complicated maneuvers required for CABG surgery, especially the anastomosis procedure.

In order to enable following the heart motion with a sufficiently high speed, the insert/compensator mechanism of the tool-orientation unit is equipped with a high frequency linear actuator, which provides

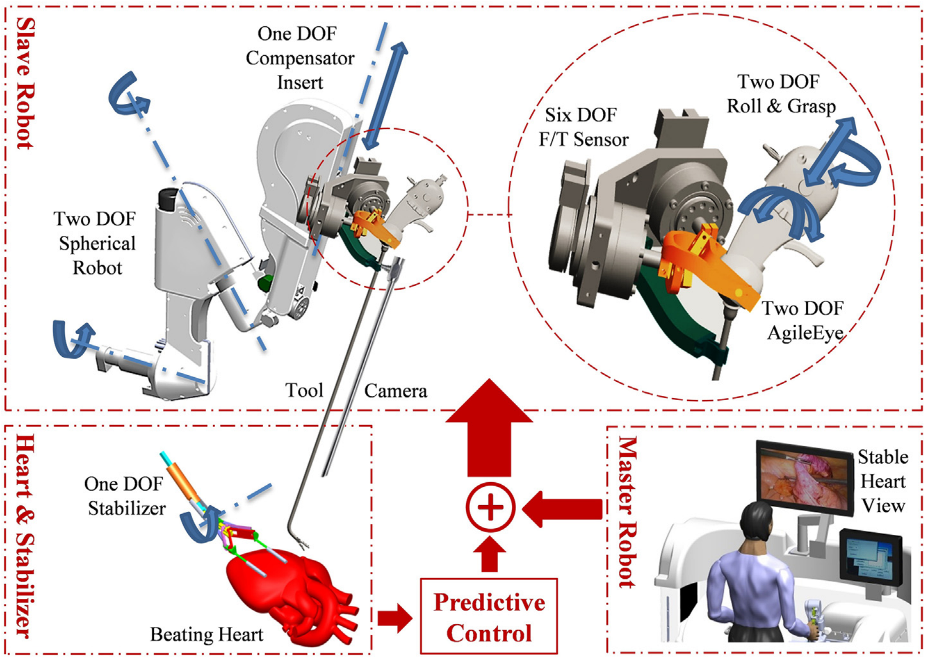


Fig. 1. Schematics of the proposed robotic beating heart surgery approach.

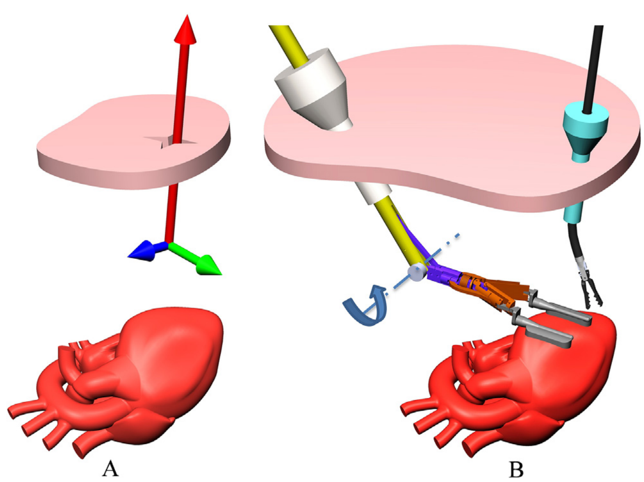


Fig. 2. (A) Schematic illustration of the relative scales of heart excursions in the normal and lateral directions, as reported by Ruszkowski et al. [44]. (B) The tool is inserted through an incision made on the abdominal wall along the normal direction of heart motion, i.e., perpendicular to the heart surface in the target area. The small lateral movements of the heart are diminished by the heart stabilizer.

the relative motion cancellation in the direction of the tool insertion. Fig. 2A illustrates the relative scales of the heart excursions in the normal and lateral directions, as reported by Ruszkowski et al. [44]. We suggest inserting the tool though an incision made on the abdominal wall along the normal direction of heart motion, i.e., perpendicular to the heart surface in the target area (Fig. 2B). This would allow the insert/compensator mechanism to cancel the normal motion of the heart completely.

We also equip the robot with a six axis force/torque sensor, just before the tool-activation unit, in order to measure the force interactions between the robot and the tool. The information provided by the sensor is used to produce a haptic feedback for the surgeon, and also to generate safety alarms for retracting the tool, in case that the compensation mechanism malfunctions.

Minimally invasive 1-DOF heart stabilizer

The proposed 1-DOF compensator only follows the heart surface excursion along the normal direction. Although being small, the lateral movements of the heart surface remain uncompensated, which can make the surgery difficult. To completely eliminate the relative motion between the robot and the heart, we use a specially designed flexible stabilizer. The fingers of this stabilizer are attached firmly to the heart surface by suction, similar to the Octopus system [33]. However, with a hinge between the proximal and distal ends of the stabilizer (Fig. 2B), it only restricts the lateral movements of the heart surface, allowing the heart to move freely in the normal direction. As a result, the proposed stabilizer would exert a much lower holding force to the heart, in comparison with the Octopus system, considering the fact that the side movements of the heart surface are very small. It has been reported that the maximum normal excursion (z direction in Fig. 2A) of the left ventricular midwall is about 12 mm while its maximum lateral displacements (y and x directions in Fig. 2A) are about 3 mm and 1 mm, respectively [44]. The stabilizer is equipped with a motion sensor which measures the dominant normal excursion of heart surface. The predictive controller uses this data to predict the future heart trajectory and send appropriate commands to the actuator of the heart motion compensator mechanism.

The stabilizer is designed as an endoscopic tool, to keep the surgery minimally invasive and eliminate the need for additional intercostal incisions. In its closed configuration, the stabilizer can pass through a 20 mm trocar (Fig. 3A). By pushing the jaw opener at the proximal end, the surgeon actuates the parallelogram mechanism at the distal end and opens the suction fingers (Fig. 3B). Then, he/she uses the aligner mechanism to revolve the suction fingers about the pivot and align them with the heart surface at the target area (Fig. 3C). By attaching the fingers to the heart surface through suction, the complex motion of the target area reduces to a pure normal excursion. During the surgery, the encoder attached to the pivot measures this excursion. After finishing the operation, the aligner and the jaw opener are pulled back to return the stabilizer into its closed configuration.

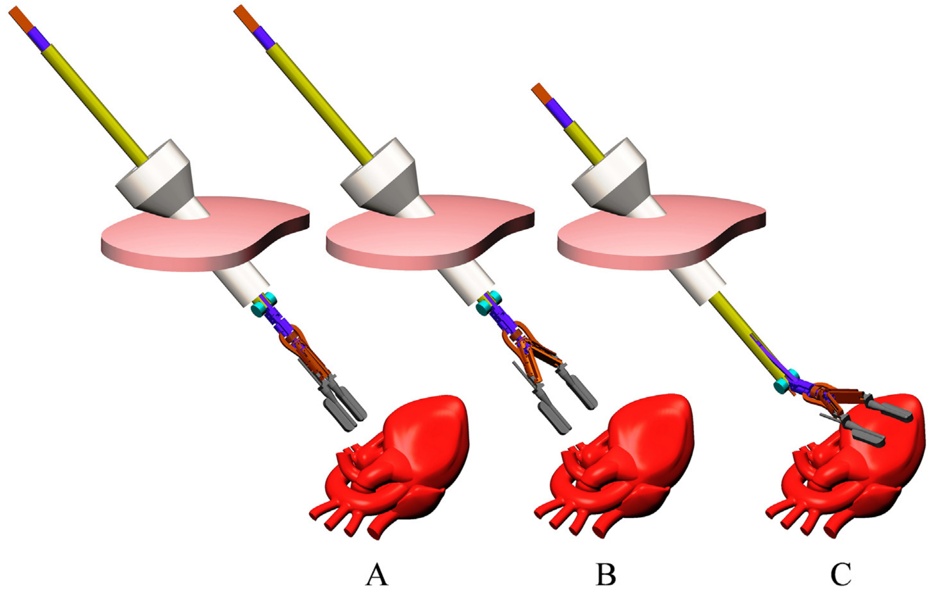


Fig. 3. The flexible endoscopic stabilizer in (A) closed, (B) open and (C) operating configurations.

Evaluation of the hypothesis

In this paper, we introduced a robotic approach for performing TECAB surgery on beating hearts. Now we are willing to evaluate the performance of the proposed system. To do so, we first analyze the surgery procedure and define the required functionalities for the robot. Then we try to analyze and quantify the requirements and provide practical solutions for them.

Slave robot: tool-orientation unit

The tool-orientation unit of the slave robot should provide sufficient workspace for TECAB surgery. Rosen et al [49,50] performed extensive in-vivo experiments and defined dexterous workspace (DWS) and extended dexterous workspace (EDWS) for laparoscopic surgeries. In an earlier work [46], we designed and developed a laparoscopic robotic arm based on EDWS. This robotic arm provided highly dexterous and precise tool manipulation capabilities inside the EDWS, which was in the form of an elliptical cone with orthogonal apex angles of 60° and 90°, and the vertex located on incision point. Moreover, the motor selection of the robot was based on general laparoscopic surgery where tools move smoothly and slowly.

Here, we intend to modify the design of this robotic arm and adapt it to be used as the tool-orientation unit of the slave robots of the beating heart robotic surgery. A similar design optimization procedure might be utilized to find the dimensions of the mechanisms of the tool-orientation unit, such that the required workspace for the TECAB surgery is achieved. The main concern in the design of the tool-orientation unit, however, is the requirement of performing jerky movements, in order to compensate the heart motion. In particular, the insert mechanism should be capable of acting as the motion compensator too. For this new functionality, the structure of the tool-orientation unit should be redesigned to account for the dynamic and vibrational effects, and its motors replaced with appropriate high-speed motors.

The structural design of the tool-orientation unit might be modified considering the dynamic parameters, e.g., the stiffness of the structure, the natural frequencies of the system, and the inertia of the moving parts. For motor selection, the speed and acceleration of the human heart and the inertial properties of the distal components are the main parameters. The heart trajectory of a human has a similar pattern to an adult pig, only differing in amplitude and heart rate. A study on pig's heart motion reported an average heart rate of 120 beats/min with an amplitude of 14 mm, maximum velocity of 0.175 m/s and maximum acceleration of 36.95 m/s^2 [40]. The compensator motor should be able to move the distal tool-activation unit, with an estimated weight of 4 kg, with the mentioned velocity and acceleration. A linear motor seems to be a good candidate for such application with its high acceleration as well as short response time, both beneficial for accurate tracking of heart trajectory. We selected the P01-37x120 motor from LinMot with maximum velocity and peak force of 3.2 m/s and 163 N, respectively [51]. This peak force is sufficient for moving the tool-activation unit with the desired acceleration. Also, the maximum velocity of the motor is about 20 times larger than the desired speed. The designed tool-orientation unit, consisting of a robotic arm with three actuators, is shown in Fig. 4A. The first two actuators are used to orient the tool and the third one, i.e., the linear motor, provides both the insertion and compensation motions.

Slave robot: tool-activation unit

The tool-activation unit of the slave robot is located distal to the compensator mechanism and therefore no extra inertial forces are applied on the actuators of the distal wrist, as well as those of the roll, and grasp DOFs. The main concern in designing the tool-activation unit is its capability of holding and manipulating the articulated laparoscopic tools and providing the necessary workspace for the wrist maneuver. To do so, we first overview the CABG surgery procedures and then analyze its most challenging tasks that should be performed robotically.

To bypass the clogged artery, both the arterial and venous vessels may be used. Surgeons preferably use Left Internal Mammary Artery (LIMA) as it directly feeds from aorta and therefore needs no proximal anastomosis. They firstly harvest the LIMA and then open the pericardium to access the blocked coronary artery. After finding the blockage, they apply proximal and distal occlusion tapes to prevent bleeding at the anastomosis site. To finish the bypass, they make a small incision in the distal coronary artery and perform end-to-side anastomosis. In the case of using an alternative graft such as saphenous vein, the last step is to suture the proximal end of the graft into the aorta [16,24,26,52].

During robotic TECAB surgery, suturing is the most intricate task. To perform anastomosis, the robot should be able to perform highly delicate and precise maneuvers of running suture, as the most common anastomosis technique [16,26], inside the limited space of thoracic cavity. In this technique, the surgeon inserts the needle perpendicular

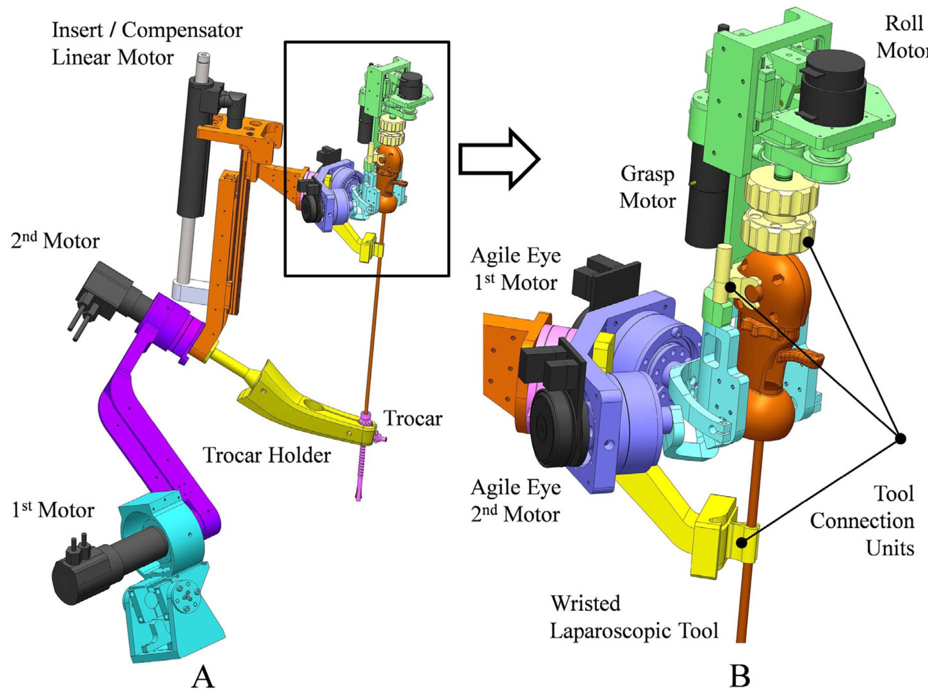


Fig. 4. The slave robot consisting of (A) tool-orientation unit and (B) tool-activation unit.

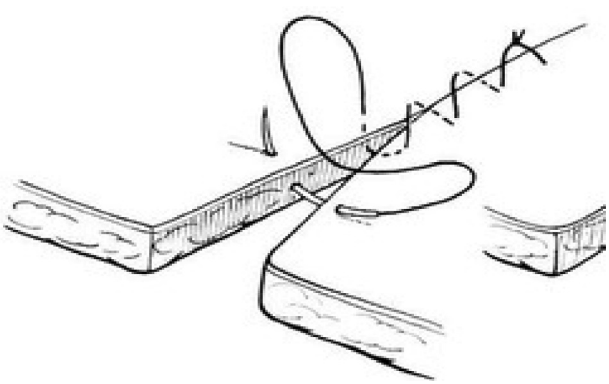


Fig. 5. Schematics of running suture.

to the target epidermis using a needle holder, and rotates it through the dermis until the needle tip exits from the contralateral side of the wound (Fig. 5). Then, he/she grasps the needle body using a forceps, held by the other hand, and pulls it out, while continues rotating the needle through its arc [53]. The next step is knot tying of the suture. This subtask is accomplished by circling the thread at the needle side a few times around the needle holder, and then, grasping the end of the thread with the needle holder and drawing it out through the thread loops.

We can model the anastomosis and the knot tying procedures with a number of simple movements. Assuming that the initial orientation of the needle with respect to the tissue is correct, the insertion of the needle into the epidermis can be achieved by linear motion of the needle holder. Then, the needle holder follows a circular trajectory and simultaneously rolls the tool tip to insert the curved needle deep into the tissue. Afterward, the forceps approaches and grasps the needle tip from the other side of the wound and continues the circular trajectory to fully extract it from the tissue. To perform the knot, the forceps should circle the needle around the needle holder for at least one turn. We modeled this trajectory by a conic motion around the needle holder. Finally, the needle holder performs a series of linear movements to completely draw the thread through the thread loops and tie the knot.

As suggested before, to optimize the 1-DOF heart motion compensation, the tool should be inserted into the body from between the rips and in a location along the normal direction of the heart motion, i.e., perpendicular to the heart surface in the target area. So, we have narrow choices for the initial orientation of the instrument. On the other hand, the space inside thoracic cavity is very limited. Therefore, to perform the CABG surgery and specially the anastomosis subtasks – which require broad and rapid maneuver of the tool tip in both position and orientation – we need articulated instruments with distal wrist and roll motion. We consider a two DOF distal wrist with about ± 90° pitch/yaw range of rotation and a continuous ± 180° distal roll. These degrees of freedom enable the surgeon to accurately perform the intricate subtasks of anastomosis at the target area on the heart surface.

One of our main concerns in the proposed surgical robotic system is its affordability for both hospital and patient. To minimize the operation cost for the patient, we propose using low cost conventional articulated laparoscopic tools, instead of expensive exclusively designed robotic instruments. A vast variety of laparoscopic instruments exist in the market. Our main criteria include the wrist DOFs and bending angle, as well as the capability of converting the instrument into a robotic tool. Compactness, availability and cost effectiveness are the next priorities for tool selection.

After analyzing the commercial laparoscopic tools, we firstly decided to use Autonomy™ Laparo-Angle™ Articulating Instrument from CambridgeEndo. The end-effecter of this tool contains a two DOF snake-like wrist with ± 90° pitch/yaw rotation, a continuous ± 180° distal roll, and a grasper, scissor, etc. at the distal end. We measured the range of motion and force requirements at the tool handle, and designed a tool-activation unit to fully activate the instrument [47]. Recently, the CambridgeEndo company went bankrupt and so we switched to SILS™ hand instruments from Covidien products, Medtronic [54]. The new instrument has similar DOFs compared with the previous one and only differs in the range of wrist motion – which is ± 80° instead of ± 90°. So we adjusted the tool-activation unit to the new tool by modifying the handle holding interface. The designed tool-activation unit, consisting of four actuators and a 2-DOF Agile Eye mechanism, is shown in Fig. 4B. Two actuators are used to drive the Agile Eye and consequently the wrist joint, and the two others actuate the roll and the grasp DOFs of the wristed tool. The final design of the tool-activation unit enjoys a modular design which makes it capable of actuating different wristed instruments by minor adjustments in the handle holding interface.

Flexible stabilizer

The 1-DOF heart stabilizer shall be equipped with a motion sensor, i.e., an encoder attached to the hinge, to measure the dominant normal excursion of heart surface. The encoder should be very small to pass through the 20 mm trocar and also accurate enough to measure the normal heart excursion with a maximum error of ± 0.5 mm. An absolute encoder is preferred over the incremental ones since the former eliminates the need for calibration in every use. Considering these requirements, we selected a very small (8 mm diameter and 3 mm width) absolute magnetic encoder, RM08S, with 12 bit positioning resolution (4096 counts per revolution) and ± 0.3° angular accuracy [48]. This accuracy is equivalent to ± 0.42 mm translational accuracy at the stabilizer fingers and hence satisfies the ± 0.5 mm accuracy requirement for measuring the heart surface motion.

We evaluated the performance of a prototype of the designed flexible stabilizer (Fig. 6A) during in-vivo animal tests. Prior to the tests, the research protocol was reviewed by the university research ethics committee which approved the compliance of the experiments with the National Code of Practice for the Care and Use of Animals for Scientific Purposes. We used the setup of Mansouri et al [55], in the Animal Surgery Laboratory of Shahid Rajaie Cardiovascular Medical and Research Center. The heart motion was measured by attaching markers to the heart of a two-year old male dog and recording the 3D trajectories of the markers using an infrared tracker [56] (Fig. 6B). The movement of the heart, stabilized using the flexible stabilizer, was compared with those of the free heart and the stabilized heart using the commercial Octopus stabilizer. Results showed that the lateral rigidity of the flexible stabilizer is sufficient to eliminate the lateral movements of the heart effectively, similar to Octopus. However, the normal excursion of the heart surface remained the same as that of the free heart, indicating that no restriction force is exerted in the normal direction to the heart surface.

Consequences of the hypothesis and discussion

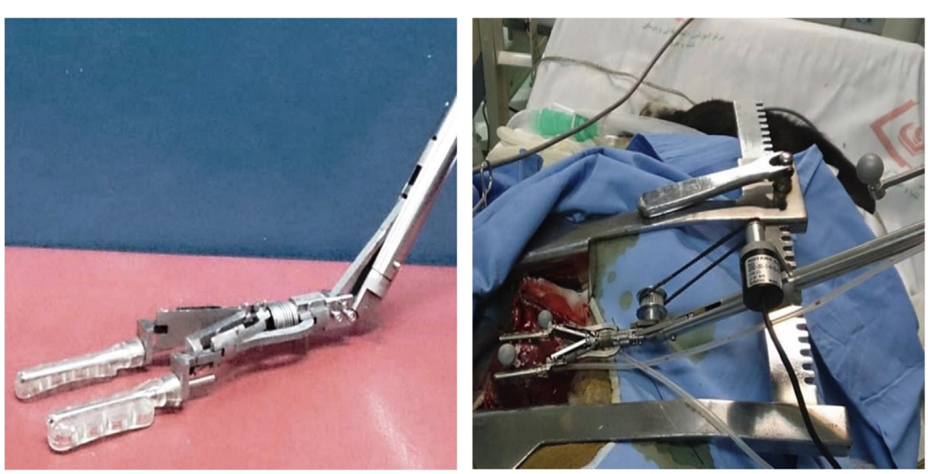
In this study, we proposed a practical solution, based on an advanced robotic system, to perform Totally Endoscopic Coronary Artery Bypass graft (TECAB) on a beating heart. We brought a compromise between two radical approaches: 1) operating on a completely immobilized beating heart with no heart motion compensation, and 2) operating on a freely beating heart with full compensation of heart motion. The available surgical robotic systems perform TECAB using the first approach; they rely on rigid stabilizers to immobilize the heart surface completely, which can damage the heart tissue. The second approach, on the other hand, is complicated technically and much expensive. Our proposed approach is to operate on a partially stabilized beating heart with unidirectional compensation of the heart motion.

Our solution for the robotic TECAB on beating hearts is both practical and cost effective. The innovative 1-DOF stabilizer resolves the problem of following the complex 3D heart motion by the robotic arm. At the same time, it induces no damage to the heart tissue since the heart surface can move freely in the dominant normal direction. Moreover, we found readily available linear motors which can afford the high forces, speeds and accelerations required for following the heart trajectory in the normal direction. The unidirectional motion compensation of the heart, however, imposes some limitations in the insertion site of the surgical tool. Considering this constraint, we designed a 4-DOF tool-activation unit to manipulate the articulated laparoscopic tools. We showed that this unit can provide the maneuverability and workspace required for the most challenging task of CABG procedure, i.e., anastomosis suturing. Finally, to minimize the operation costs, we proposed using low cost conventional articulated laparoscopic tools, as the surgical tools of TECAB.

Our proposed solution for robotic TECAB on beating hearts is promising. However, further research work should be performed to assess its applicability in clinical practice. The efficacy of the designed flexible heart stabilizer was examined in a single in-vivo animal test. More experiments should be conducted in future to evaluate the effectiveness of the stabilizer in restricting the heart lateral movements, as well as measuring the normal excursion of the heart surface accurately. Moreover, a prototype of the tool-orientation unit, with a unidirectional compensator equipped with the selected linear motor, is under fabrication to be examined experimentally. Similarly, we are in the process of developing a prototype of the tool-activation unit of the slave robot to assess its efficiency in performing the different tasks involved in the CABG procedure. Finally, the whole robotic system, with all subsystems assembled together, is planned to be tested on a beating heart simulator, and then in animal tests.

Conflict of interest

None.



A B

Fig. 6. The flexible stabilizer: (A) the fabricated prototype, (B) during in-vivo animal test.

Acknowledgement

This study was supported by grants from Iran National Science Foundation (INSF), Research Centre for Biomedical Technologies and Robotics (grant number 29929), and Rajaie Cardiovascular Medical and Research Centre. The technical support of Prof Alireza Alizadeh Ghavidel and Sina Robotics and Medical Innovators Company is appreciated.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.mehy.2019.02.005.

References

[1] Murphy SL, Xu J, Kochanek KD, Curtin SC, Arias E. Deaths: final data for 2015. Natl Vital Stat Reports 2017;66:1–75.
[2] Bebek O. Robotic-assisted beating heart surgery. Case Western Reserve University; 2008.
[3] Narum E. Heartbeat synchronization for the establishment of a virtual surgical reality. Norway: University of Science and Technology; 2004.
[4] Rotella J. Predictive tracking of quasi periodic signals for active relative motion cancellation in robotic assisted coronary artery bypass graft surgery. Case Western Reserve University; 2005.
[5] Moller CH, Penninga L, Wetterslev J, Steinbrüchel DA, Gluud C. Off-pump versus on-pump coronary artery bypass grafting for ischaemic heart disease. Cochrane Database Syst Rev 2012;3:CD007224.
[6] Gao C, Yang M. Robotic coronary bypass graft on beating heart. In: Gao C, editor. Robot. Card. Surg., Dordrecht: Springer Netherlands; 2014, p. 111–33.
[7] Dwivedi J, Mahgoub I. Robotic surgery: a review on recent advances in surgical robotic systems. Florida Conf Recent Adv Robot 2012:1–7.
[8] Wimmer-greinecker G, Ph D, Deschka H, D M, Aybek T, D M, et al. Current status of robotically assisted coronary revascularization 2004;188:76–82. doi: 10.1016/j.amjsurg.2004.08.007.
[9] Benetti FJ, Ballester C, Sani G, Doonstra P, Grandjean J. Video assisted coronary bypass surgery. J Card Surg 1995;10:620–5. https://doi.org/10.1111/j.1540-8191.1995.tb00651.x.
[10] Ruel M, Une D, Bonatti J, McGinn JT. Minimally invasive coronary artery bypass grafting: is it time for the robot? Curr Opin Cardiol 2013;28:639–45. https://doi.org/10.1097/HCO.0b013e3283653fd1.
[11] Ruel M, Shariff MA, Lapierre H, Goyal N, Dennie C, Sadel SM, et al. Results of the minimally invasive coronary artery bypass grafting angiographic patency study. J Thorac Cardiovasc Surg 2014;147:203–8. https://doi.org/10.1016/j.jtcvs.2013.09.016.
[12] Kikuchi K, Mori M. Minimally invasive coronary artery bypass grafting: a systematic review. Asian Cardiovasc Thorac Ann 2017;25:364–70. https://doi.org/10.1177/0218492317692465.
[13] Benetti F, Mariani MA, Sani G, Boonstra PW, Grandjean JG, Giomarelli P, et al. Video-assisted minimally invasive coronary operations without cardiopulmonary bypass: a multicenter study. J Thorac Cardiovasc Surg 1996;112:1478–84. https://doi.org/10.1016/S0022-5223(96)70006-5.
[14] Birla R, Patel P, Aresu G, Asimakopoulos G. Minimally invasive direct coronary artery bypass versus off-pump coronary surgery through sternotomy. Ann R Coll Surg Engl 2013;95:481–5. https://doi.org/10.1308/003588413X13629960047119.
[15] Moss E. Robotic cardiac surgery: current status and future directions. Robot Surg Res Rev 2014;2014:27–36.
[16] Dogan S, Aybek T, Andreßen E, Byhahn C, Mierdl S, Westphal K, et al. Totally endoscopic coronary artery bypass grafting on cardiopulmonary bypass with robotically enhanced telemanipulation: report of forty-five cases. J Thorac Cardiovasc Surg 2002;123:1125–31.
[17] da Vinci® Surgery: Minimally Invasive Surgery n.d. http://www.davincisurgery.com/.
[18] Hagn U, Nickl M, Jörg S, Passig G, Bahls T, Nothhelfer A, et al. The DLR MIRO: a versatile lightweight robot for surgical applications. Ind Robot An Int J 2008;35:324–36.
[19] Beasley RA. Medical robots: current systems and research directions. J Robot 2012;2012:1–14.
[20] Gidaro S, Altobelli E, Falavolti C, Bove AM, Ruiz EM, Stark M, et al. Vesicourethral anastomosis using a novel telesurgical system with haptic sensation, the Telelap Alf-X: a pilot study. Surg Technol Int 2014;24:35–40.
[21] Senhance Surgical System n.d.
[22] Mohr FW, Falk V, Diegeler A, Walther T, Gummert JF, Bucerius J, et al. Computer-enhanced “robotic” cardiac surgery: Experience in 148 patients. J Thorac Cardiovasc Surg 2001;121:842–53. https://doi.org/10.1067/MTC.2001.112625.
[23] Lee JD, Srivastava M, Bonatti J. History and current status of robotic totally endoscopic coronary artery bypass. Circ J 2012;76:2058–65. https://doi.org/10.1253/circj.CJ-12-0981.
[24] Canale LS, Mick S, Mihaljevic T, Nair R, Bonatti J. Robotically assisted totally endoscopic coronary artery bypass surgery. J Thorac Dis 2013;5:641–9.
[25] Gobolos L, Ramahi J, Obeso A, Bartel T, Traina M, Edris A, et al. Robot-assisted totally endoscopic coronary bypass surgery. Indian J Thorac Cardiovasc Surg 2018;34:94–104.
[26] Falk V, Jacobs S, Gummert JF, Walther T, Mohr FW. Computer-enhanced endoscopic coronary artery bypass grafting: the da Vinci experience. Semin Thorac Cardiovasc Surg 2003;15:104–11.
[27] Lichtenberg A, Hagl C, Harringer W, Klima U, Haverich A. Effects of minimal invasive coronary artery bypass on pulmonary function and postoperative pain. Ann Thorac Surg 2000;70:461–5. https://doi.org/10.1016/S0003-4975(00)01505-8.
[28] Karpuzoglu OE, Ozay B, Sener T, Aydin NB, Ketenci B, Aksu T, et al. Comparison of minimally invasive direct coronary artery bypass and off-pump coronary artery bypass in single-vessel disease. Heart Surg Forum 2009;12:E39–43. https://doi.org/10.1532/HSF98.20081068.
[29] Lapierre H, Chan V, Sohmer B, Mesana TG, Ruel M. Minimally invasive coronary artery bypass grafting via a small thoracotomy versus off-pump: a case-matched study☆☆☆. Eur J Cardio-Thoracic Surg 2011;40:804–10. https://doi.org/10.1016/j.ejcts.2011.01.066.
[30] Rogers CA, Pike K, Angelini GD, Reeves BC, Glauber M, Ferrarini M, et al. An open randomized controlled trial of median sternotomy versus anterolateral left thoracotomy on morbidity and health care resource use in patients having off-pump coronary artery bypass surgery: The Sternotomy Versus Thoracotomy (STET) trial. J Thorac Cardiovasc Surg 2013;146(306–316):e9https://doi.org/10.1016/J.JTCVS.2012.04.020.
[31] Rabindranauth P, Burns JG, Vessey TT, Mathiason MA, Kallies KJ, Paramesh V. Minimally invasive coronary artery bypass grafting is associated with improved clinical outcomes. Innov Technol Tech Cardiothorac Vasc Surg 2014;9:421–6. https://doi.org/10.1097/IMI.0000000000000110.
[32] Baishya J, George A, Krishnamoorthy J, Muniraju G, Chakravarthy M. Minimally invasive compared to conventional approach for coronary artery bypass grafting improves outcome. Ann Card Anaesth 2017;20:57–60.
[33] Gagne J, Bachta W, Renaud P, Piccin O, Laroche É, Gangloff J. Beating heart surgery: comparison of two active compensation solutions for minimally invasive coronary artery bypass grafting. In: Garbey M, Lee Bass B, Berceli S, Collet C, Cerveri P, editors. Comput. Surg. Dual Train. Comput. Robot. Imaging, New York, NY: Springer New York; 2014, p. 203–10.
[34] Lemma M, Mangini A, Redaelli A, Acocella F. Do cardiac stabilizers really stabilize? Experimental quantitative analysis of mechanical stabilization. Interact Cardiovasc Thorac Surg 2005;4:222–6.
[35] Cattin P, Dave H, Grünenfelder J, Szekely G, Turina M, Zünd G. Trajectory of coronary motion and its significance in robotic motion cancellation. Eur J Cardio-Thoracic Surg 2004;25:786–90.
[36] Gao C, Yang M, Wu Y, Wang G, Xiao C, Zhao Y, et al. Early and midterm results of totally endoscopic coronary artery bypass grafting on the beating heart. J Thorac Cardiovasc Surg 2011;142:843–9.
[37] de Cannière D, Wimmer-Greinecker G, Cichon R, Gulielmos V, Van Praet F, Seshadri-Kreaden U, et al. Feasibility, safety, and efficacy of totally endoscopic coronary artery bypass grafting: Multicenter European experience. J Thorac Cardiovasc Surg 2007;134:710–6.
[38] Trejos AL, Salcudean SE, Sassani F, Lichtenstein S. On the Feasibility of a Moving Support for Surgery on the Beating Heart. In: Taylor C, Colchester A, editors. Med. Image Comput. Comput. Interv. – MICCAI’99, Berlin, Heidelberg: Springer Berlin Heidelberg; 1999, p. 1088–97.
[39] Nakamura Y, Kishi K, Kawakami H. Heartbeat synchronization for robotic cardiac surgery. Proc. 2001 ICRA. IEEE Int. Conf. Robot. Autom. (Cat. No.01CH37164), vol. 2, IEEE; n.d., p. 2014–9.
[40] Bebek Ö, Cavusoglu MC. Intelligent control algorithms for robotic-assisted beating heart surgery. Robot IEEE Trans 2007;23:468–80.
[41] Yuen SG, Kettler DT, Howe RD. Robotic motion compensation for beating intracardiac surgery. 2008 10th Int. Conf. Control. Autom. Robot. Vis., IEEE; 2008, p. 617–22.
[42] Ginhoux R, Gangloff J, de Mathelin M, Soler L, Sanchez MMA, Marescaux J. Active filtering of physiological motion in robotized surgery using predictive control. IEEE Trans Robot 2005;21:67–79.
[43] Cuvillon L, Gangloff J, de Mathelin M, Forgione A. Toward robotized beating heart TECABG: assessment of the heart dynamics using high-speed vision. Med Image Comput Comput Assist Interv 2005;8:551–8.
[44] Ruszkowski A, Mohareri O, Lichtenstein S, Cook R, Salcudean S. On the feasibility of heart motion compensation on the daVinci® surgical robot for coronary artery bypass surgery: implementation and user studies. Proc – IEEE Int Conf Robot Autom 2015:4432–9.
[45] Mansouri S, Farahmand F, Vossoughi G, Ghavidel AA. A hybrid algorithm for prediction of varying heart rate motion in computer-assisted beating heart surgery. J Med Syst 2018.
[46] Alamdar A, Mirbagheri A, Farahmand F, Durali M. Design of a 4 DOF laparoscopic surgery robot for manipulation of large organs. Stud. Health Technol. Inform. 2012;173:8–12.
[47] Hanifeh S, Alamdar A, Farahmand F, Mirbagheri A. An Adapting Mechanism to Manipulate Manual Wristed Laparoscopic Instruments by a Robotic Surgery System. 4th Int. Conf. Control. Dyn. Syst. Robot., 2017, p. 1–8.
[48] RM08 super small non-contact rotary encoder n.d. https://www.rls.si/en/rm08-super-small-non-contact-rotary-encoder (accessed February 23, 2018).
[49] Rosen J, Brown JD, Chang L, Barreca M, Sinanan M, Hannaford B. The BlueDRAGON – a system for measuring the kinematics and dynamics of minimally invasive surgical tools in-vivo. Proc. 2002 IEEE Int. Conf. Robot. Autom. (Cat. No. 02CH37292), vol. 2, IEEE; 2002, p. 1876–81. doi: 10.1109/ROBOT.2002.1014814.
[50] Lum MJH, Rosen J, Sinanan MN, Hannaford B. Kinematic optimization of a spherical mechanism for a minimally invasive surgical robot. IEEE Int. Conf. Robot.

Autom. 2004. Proceedings. ICRA '04. 2004, IEEE; 2004, p. 829–834, Vol. 1.
[51] PS01-37x120-C n.d. http://shop.linmot.com/E/ag1000.37.121/linear-motors/linear-motors-p01-37/stators-ps01-37x120/ps01-37x120-c.htm (accessed February 7, 2018).
[52] Shahani R. Coronary artery bypass grafting technique. MedScape 2017. http://emedicine.medscape.com/article/1893992-technique#c1 (accessed May 12, 2018).
[53] Kantor J, editor. Chapter 5.3. The Simple Running Suture. Atlas Suturing Tech. Approaches to Surg. Wound, Laceration, Cosmet. Repair, 2016, p. 182–6.
[54] Medtronics SILSTM HAND INSTRUMENTS n.d. http://www.medtronic.com/covidien/en-us/products/hand-instruments-ligation/sils-hand-instruments.html (accessed April 23, 2018).
[55] Mansouri S, Farahmand F, Vossoughi G, Ghavidel AA, Rezayat M. Feasibility of infrared tracking of beating heart motion for robotic assisted beating heart surgery. Int J Med Robot Comput Assist Surg 2017;14:1–12.
[56] Houshmand A. Design, fabrication, and experimental study of a flexible cardiac stabilizer for beating heart robotic. Sharif University of Technology, International Campus, Kish Island, Iran, 2016.