BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 58, No. 2, 2010
DOI: 10.2478/v10175-010-0030-6

Robin heart progress – advances material and technology in surgical robots

Z. NAWRAT*

Foundation for Cardiac Surgery Development, 345a Wolności St., 41-800 Zabrze, Poland

Abstract. The paper presents the current state of works conducted by the Zabrze team under the Robin Heart surgical robot and the Robin Heart Uni System mechatronic surgical tools project as a example of introducing technology and materials advances for progress in surgical robots. The special intention of the author is to show the review of the current and futuristic medical robots needs in the area of material science.

Key words: medical robots, surgical tools.

1. Introduction

The market for medical tele-manipulators used in surgery is expanding very dynamically. The development of medical robotics results in the construction of tools of direct via technology tele-medical contact with patients and medical personnel. The robotic systems are information systems and as such they have the ability to interface and integrate many of technologies being developed for and currently used in the operating room.

The surgery is a complex procedure requiring precise control of position and force. About 4 millions of minimally-invasive surgeries are performed in the world every year. These procedures are carried out by means of special instruments inserted through small incisions in the patient's body. The aim is to limit the operative field and spare surrounding tissue, which would be damaged if a traditional surgical technique is used. The number of endoscopic procedures, less invasive than traditional surgery, performed through natural orifices in the patient's body, or through special openings called ports, is on the rise. Many studies have shown that laparoscopic procedures result in decreased hospital stays, a quicker return to the workforce, decreased pain, better cosmesis, and better postoperative immune function. The success of the procedures largely depends on the instruments used. Unfortunately, typical endoscopic (laparoscopic) instruments reduce precision and make the surgery more difficult because they add to hand tremor and almost completely eliminate the natural sense of touch.

Robot is intended to keep the surgeon in the most comfortable, dexterous and ergonomic position. The basic principle of manipulator construction is that of a serial architecture of joints and links with a fixed remote centre in corporeal wall. The surgeon control via a human-machine the movements of tolls. The main task of robot (Master-Slave teleoperator) is reliable mapping of surgeon hand movements (setting of position/velocity/acceleration of other physical quantity) onto the movements of tool arm, through calculation of control signals for its motors.

Contemporary the history of medical robotics in surgery has been created by the da Vinci (Intuitive Surgical, in Mountain View, Calif., IS) & Zeus (Computer Motion Inc. of Goleta, Calif., CM, currently merged companies), but in several laboratories and universities the next generation of surgical robots are waiting for crossing from laboratory to surgery room. The Foundation of Cardiac Surgery Development (FCSD) realizes project of polish robot useful for cardiac surgery (Fig. 1). The multidisciplinary team prepared families of robot prototypes named Robin Heart and mechatronic tools. New, semi-automatic tools are in the process of emerging-our Robin Heart Uni System. It is most possible that in the future current tele-operators will be replaced by adaptive robots. Future systems might include the ability for a surgeon to program the surgery and merely supervise as the robot performs most of the tasks.

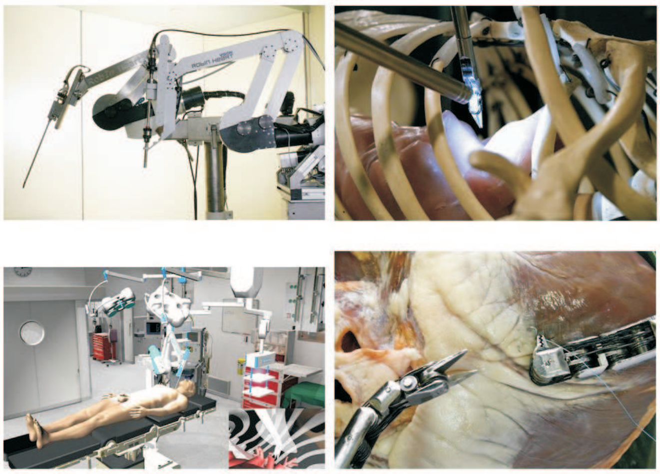

Fig. 1. Robin Heart – physical and computer models

*e-mail: nawrat@frk.pl

2. Surgery robots – problems

The future of robotic surgery has significant potential what verified in many clinical applications. Endoscopic microsurgery is difficult to perform with standard hand held instruments but till now robotically assisted did not solve all the problems, such the high cost, relatively large size, a lack of compatible instruments. Some of the more prominent limitations involve the technical and mechanical nature of the equipment.

The most crucial limitations today remain related to: new smart tools, stabilization procedure, suture technique, preoperative planning and intraoperative navigation, and force feedback.

The development process needs new technologies, new materials, new constructions and design.

If the cost of these systems remains high and they do not reduce the cost of routine procedures, it is unlikely that there will be a robot in every operating room and thus unlikely that they will be used for routine surgeries [1]. As scientists seek to improve the versatility and utility of robotics in surgery, some are attempting to miniaturize the robots. For example, the University of Nebraska Medical Center has led a multi-campus effort to provide collaborative research on mini-robotics among surgeons, engineers and computer scientists.

An average operation uses up \$1,500 in consumable tools. Da Vinci lists for \$1.3 million (The new da Vinci HD SI released in April, 2009 currently sells for \$1.75 million), and IS economist estimates that high-volume hospitals will spend another \$525,000 per year for service contracts and parts for the three units. The da Vinci's robotic surgical instruments have a fixed usage life of 10 procedures per instrument. This disadvantage is related to material and construction used in tools [2].

Current instruments have restricted degrees of motion; most have 4 degrees of freedom DOF (motion), whereas the human wrist and hand have 7 DOF. The very important problem is developing the driving system of the wrist and the gripper. The following systems are possible: the follower-based system and the string system. For the follower drive they are as follows: from $\pm 20^0$ to $\pm 50^0$ – just like in the Zeus robot. For the string drive they usually are $\pm 90^0$ – just like in DaVinci robot and the Robin Heart 1. The Robin Heart has 7 DOFs – it is redundant. In Robin Heart 3 and Uni Tools 1 the combination of follower and string system were introduced. The special relation between the elasticity and stiffness in Robin Heart Uni Tools 0 was reached using connection of stainless steel and Nitinol.

The development of robotics is spurring interest in new tissue anastomosis techniques, improving laparoscopic instruments, and digital integration of already existing technologies. Although these systems have greatly improved dexterity, they have yet to develop the full potential in instrumentation or to incorporate the full range of sensory input. More standard mechanical tools and more energy directed tools need to be developed. Some authors also believe that robotic surgery can be extended into the realm of advanced diagnostic testing with the development and use of ultrasonography, near infrared, and confocal microscopy equipment. Many laboratories are currently working on systems to relay touch sensation from robotic instruments back to the surgeon and on improving current methods and developing new devices for suture-less anastomoses [1].

Due to fixed entry points of the instruments in the abdominal wall the degrees of freedom are reduced, the movements are mirrored and scaled. The coupling between observation and manipulation, the hand-eye coordination is disturbed, tactile information about tissue properties partially, due to friction and the poor ergonomic design of instruments, lost. For laparoscopic procedures special sewing devices, ligating instruments, knot pushers, clips and clip appliers have been developed. The clamp is an essential tool during surgery where blood flow to an organ must be stopped or controlled. There is a need for secure and easy methods for suturing in laparoscopic surgery. Laparoscopic suturing can be done with a suture, using automatic sewing devices or clips. Knotting instruments require a two forceps technique, while for sewing devices one working channel is enough. The future is open for semi-automatic tools for MIS. As a example, Medtronic, Inc. has introduced the world's first minimally-invasive epicardial lead placement tool [3].

There has been a tremendous interest in the development of anastomotic devices for coronary surgery. The Requirements of Anastomoic Devices include reproducibility, ease of use and a short anastomotic time (< than 1 minute). There are manual and automatic anastomotic devices such Heartstring Aortic Occluder™from Guidant, the Enclose™device from Novare Medical, the Symmetry™Bypass System Aortic Connector developed by St. Jude Medical, Corlink™from CardioVations™, Coalescent U-CLIP™. The Passport™automatic proximal device consists of an integrated system which performs the aortotomy, delivers the graft to the aorta and deploys a stainless steel connector end-to-side the graft using one delivery device. The stainless steel stent (more rigid than Nitinol) creates a widely patent anastomosis. Another proximal anastomotic device is the Magnaport from Ventrica. This is also a one step anastomotic device using rare earth magnets. Coalascent Surgical™has developed a automatic proximal anastomotic device, called the Spyder based on their proprietary Nitinol (nickel-titanium alloy) clip technology. The SPYDER® Device provides fast, automated proximal anastomotic connection by simultaneous delivery of 6 U-CLIP devices without the use of a side-biting clamp or second manipulation of the aorta. The JoMed Solem connector consists of a stented "T" shape PTFE graft connected to the internal mammary artery. Magnetic Vascular Positioner (MVP), developed by Ventrica (received CE Mark approval in February 2002), use magnetic attraction to form an instantaneous self-aligning, self-sealing connection between two blood vessels. The elliptical magnets are placed inside the conduit and native vessel. In total endoscopic coronary artery bypass, or TECAB, a distal automatic device could be critical in evolving the endoscopic procedure.

Currently the Ventrica device is being modified for deployment in a robotic environment. Finally, in multi-vessel totally endoscopic coronary artery bypass or multi-vessel TECAB procedures, distal anastomotic devices are predicted to make a major contribution. Most minimally invasive procedures in the future will be facilitated by the automated anastomotic devices. Till now, the cost of these devices are high and they are not so popular. This short review shows the wide range of problems for automation the surgery procedures [3].

Cardiac surgery methods have made tremendous advances in the last years. Material inserted in blood system should not cause irreversible damages of proteins' structure, blocking of enzymes' activity, changes of electrolyte's composition, damages and releasing of the blood cells' contents, blood clotting, initiation of toxic, immunological and mutagenic reactions. On the basis of the *in vitro* tests of the implants made from AISI 316L steel used in bone and maxillo-facial surgery it was found out that passive-carbon coating on surfaces guarantees to the implants a very good resistance to the pitting, stress, crevice corrosion and demonstrated a good biotolerance. The deposition process of the carbon coating, using rf PACVD method, was carried out at the Institute of Materials Engineering of the Technical University of Lodz (S. Mitura and P. Niedzielski). The robot Robin Heart 1, in this type these NCD (Fig. 1) have been used on element performed at the Technical University of Lodz, have been designed by Podsedkowski/Nawrat [4].

The degree of freedom DOF are driven by electric, brushless motor. The second and third DOFs are driven by brushless motors, roller screws and system of strings. In order to enable sterilizing of the manipulator, the construction makes possible fast and not complicated disconnection the drive part of the bunch from the manipulating part. The separable part does not contain any elements requiring lubrication. Robot consists of many small elements, given under relatively huge load (some millimeters of diameter of wheel, with half millimeters strings, shifting elements oneself in relation to itself of etc.). The experience in clinical beating heart cases has demonstrated the importance of small instrumentation to successfully complete these procedures. The working tips of microsurgery instruments must be smaller than 5 mm in order to not obscure the small endoscopic field of view and efficient maneuver in the small space within the chest.

Desirable high precision and persistence of device demands proper selection of materials used. Success of settlement among requirement of large endurance and suitable constructional guilds demands uses often modification of surface of material. In Robin Heart 1 model test of use of layer NCD for diminution of friction executed among shifting oneself elements nipple for tool. Ending of tool working on tissues and in environment of blood for utilization bioactive NCD properties will be covered NCD layer. Application tests of refining layers are further driven and suitable tests will allow to verify the solutions [4].

Robots can damage during operation. For example N. oliakos et al. [5] report a rare case of a da Vinci robotic arm failure during a laparoscopic robot-assisted radical prostatectomy. The articulation joint of an Endowrist needle driver was broken and positioned at such an angle that made it impossible to remove through the trocar. In addition, it was later discovered that a small piece of the instrument was detached and remained inside the abdomen of the patient without even having been identified on subsequent radiological evaluation.

Micro technologies are attractive for use in surgical applications, since the high functional density enables new ways of directly interacting with human tissue, both in terms of sensing and actuating. The application of micro technologies to enhance laparoscopic instruments with micro-sensors has been investigated world-wide during the last two decades, with emphasis on tactile sensor technologies, but sensory enhanced tactile instrumentation has not been introduced into clinical use yet. Several technical approaches have been followed for obtaining tactile information through microsensor enhanced instruments. The vibrotactile sensor applies vibration to the tissue to be examined and quantifies the tissue properties by changes of the resonance frequency. Multiple force sensors arranged in an array are capable of detecting the shape of structures. The novel sensor principle based on the deformation of electrically conductive polymers can be used. Optomechanical force sensors seem a suitable solution for force sensing in medical instruments, laparoscopic graspers and a MRI-compatible hand-force sensor. Miniaturization is feasible and the sensors can be built inside the structure of the instrument leading to robust mechanical properties. The light source and detection electronics can be left outside and only a glass fiber is needed to make the connection between sensor and read-out. Through the application of micro technologies, novel surgical devices are able to interact with delicate tissue and structures of the human body in a more sophisticated way, both in terms of sensing and actuating [6].

3. Robin Heart

Robin Heart (www.robinheart.pl) is the name of the family of several robots that have been designed and constructed by the Foundation for Cardiac Surgery Development in Zabrze since 2000 (Fig. 1). The outcome of interdisciplinary works is presented by several models and prototypes that differ, for example, in the concept of control and working mode at the operating table. The robots have a segmented structure, which allows to set them up for different types of operations.

The cardiac surgery robot is a copying tele-manipulator that consists of two or more arm tools and one camera-holding tool. The working end of the tool affixed to the arm performs different tasks (gripping device, scissors, and coagulation knife). The kinematical structure of the manipulator consists of the arm (positioning) and the cluster (orientation of the tip). The supervision and control is achieved mainly by means of visual observation and the movement actuator in the control console. The master console consists of 2-dimensional monitor where the surgeon views the image; foot pedals to control electrocautery, instrument/camera arm clutches, and master control grips that drive the servant robotic arms at the patient's side. The Robin Heart Shell console is equipped with a consulting program that makes it possible to obtain all patients diagnostic information during the operation, as well as elements of operation planning on the screen. The virtual operating theatre introduced in our laboratory allows surgeons to train some elements of an operation, check the best placement of the ports in order to avoid internal collisions. Exhausted by 3-D visualisation, this system can be helpful in planning of an operation on a given patient.

The Robin Heart manipulator has very good and relatively large working space, in which surgeon can select small subspace with very good isotropic kinematics' properties for manipulating of objects with good position accuracy. System was verified both functionally and technically. Standard technical evaluation allowed to estimate the value of positioning resolution equal 0.1 mm.

The mile stone of the project was an animal experiment, carried out in January 2009 (Figs. 1–3). The operations were performed on pigs at the Centre of Experimental Medicine, the Silesian Medical University in Katowice with the assistance of cardiac surgeons (Romuald Cichoń, Joanna Śliwka, Grzegorz Religa, Michał Zembala). In the course of the experiments our surgeons controlled the robotic arms from the console placed in a separate room next to the operating theater. The control handle has several buttons which are activated after pressing the pedal. Thus, it is possible to simultaneously control the position and the functioning of the tools and the endoscopic camera. The goal of these experiments was to show the constructors the area of indispensable changes which will be introduced to worked out devices before study of technology of serial production and clinical initiating. Robin Heart system experiment carried out on pigs allowed to verify many aspects of very complex project and was the source of hints for future development. In the course of the animal experiment the surgical task achieved in the abdominal space was cholecystectomy, and in the chest and heart; the repair of heart valves (with extracorporeal circulation).

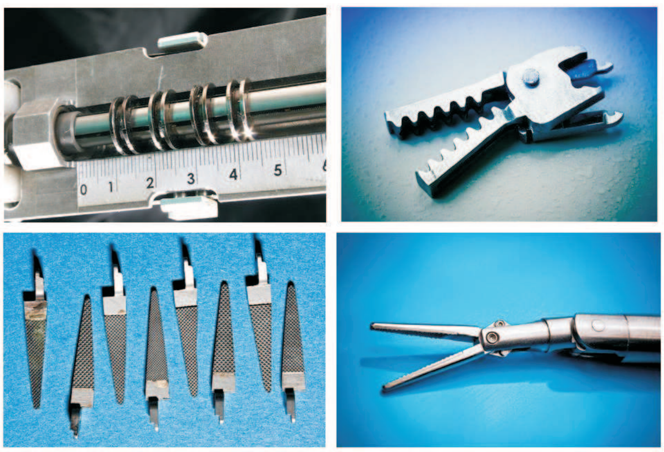

Fig. 2. NCD covered and ceramic elements of tools

As a conclusion, from the experiment users (surgeons) have expressed a good opinion on the ergonomics and possibilities of controlling the robotic arms by means of the Robin Heart Shell console. The opportunities of operating by means of the Robin Heart Uni System mechatronic tool are very promising, as it may be mounted on the robot's arm or controlled manually.

Fig. 3. The animal experiment

It was recommended that special friction lining should be used to improve needle holder so essential at the sewing stage. We decided to use the commercially available ceramic plate with special surface designed for needles keeping. Application of several kind of surface modification the ends of tools for durability and functional reason have been tested. The special kind of polymers for active biotolerance and drug release are tested for clamps and staple. The special kind of surface nanolayer modification is tested for improve the durability and functional characteristic surgery tools..

The Robin Heart Vision robot as an arm for controlling the position of the endoscopic camera is viable and ready for clinical implementation.

The Robin Heart family of Polish robots has a chance of becoming a commonly used high-tech technical and telemedical system facilitating the performance of some parts of operations in minimally invasive, precise manner, safe for the patient and the surgeon.

We plane the first clinical application of endocamera arm: Robin Heart Vision, robotically controlled in 2010, the first operation performed by Robin Heart in 2011. Based on Robin Heart project development, currently our team works on system AORobAS – Artificial Organs Robotically Assisted Surgery artificial organs implantation, services, repair, exchange, removing.

4. Conclusions

Worldwide robotically-assisted surgery systems equipment shipment markets are set to have rapid growth. Markets at $626.5 million in 2007 are anticipated to reach $1 billion in 2008 and are forecast to go to $14 billion by 2014. Growth comes because the technology is mature and the technology works. The MIS surgeries are accurate and less invasive that alternative surgical methods, creating market opportunity [7].

The da Vinci won federal approval in 2000, making it the only low-trauma surgical robot on the market. Since then, more than 1300 have been installed at hospitals worldwide, at a cost of $1.5 million apiece. Doctors worldwide perform over 100,000 da Vinci procedures per year, from bypasses to prostatectomies to hysterectomies.

To make robotically-assisted surgery more widely acceptable the operation has to be easier and more attractive for the end user, i.e. the surgeon (new tools, pre-planning, advisory system), and less expensive for the hospital owner [2].

Potential applications of robotics in cardiac surgery includes: aortic valve replacement (standard or percutaneous technology); tricuspid valve repair; descending thoracic aortic surgery; transmyocardial laser revascularization; ventricular septal defect, patent ductus arteriosus, coarctation; intramyocardial delivery platform for biological agents such as stem cells, molecular therapeutics, genetic vectors and AORobAS – Artificial Organs Robotically Assisted Surgery.

Bioengineering and surgery robotics waits for persistence, biocompatible materials presenting different desirable biophysical and technical properties.

Acknowledgements. The Robin Heart project has been financed within the frameworks of KBN 8 T11E 001 18 research project, PW-004/ITE/02/2004 commissioned project and by the Foundation for Cardiac Surgery Development, as well as many sponsors. The Robin Heart Uni System project is conducted under R13 033 01 development funds. The authors would like to take this opportunity to thank all of the people who have contributed to our achievements. Out of the immense feeling of respect, I would like to mention my masters and colleagues, starting with Zbigniew Religa (without whom there would have been no project at all), Leszek Podsędkowski, Krzysztof Mianowski and Robin Heart team: Paweł Kostka, Zbigniew Małota, Wojciech Dybka, Kamil Rohr, Wojciech Sadowski, Piotr Wojtaszczyk, Mariusz Jakubowski, Adam Klisowski, and other surgeons Romuald Cichoń and Joanna Śliwka.

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