回転ユニットの本体への装着について、当該実験環境で用いたカメラ映像が低解像度であるためピン位置の特定が困難となる状況も見られたが、当初予定したどおりに装着が可能であった。ファントム表面走査について、回転中心をプローブ表面に固定したままの探索走査を可能とすることが明らかになった。これらのことから、より統合的な環境での評価として、動物実験での有用性評価を実施することとした。

２．動物実験

上記評価１の結果をうけ、ブタ腹腔内において、装置の有用性を実践的に評価するための実験を行った。本実験では、装置の有用性を明らかにするため、実際のブタ肝臓に対して静脈走査を繰り返し実施した。また、その時の動作を解析し、必要な動作域についての検討を改めて実験的に行うことを目的とする。

添付資料に実験環境および実験結果などを図表にて示す。以下に得られた結果について述べる。まず、試作機の有する回転中心を超音波プローブ接触面とする機構は、静脈探索を容易にすることが確認された。より具体的には、術者は試作機をほぼ固定した状態で、ボタン操作によってプローブ先端の姿勢を変更できた。これにより安定した超音波画像が取得可能であり、よって探索を容易に出来たと考えられる。ロボットの動作域は本実験において十分であった。ロボットの姿勢は探索部位へのアプローチ前におおよその決定を行い、肝臓表面へ接触後は主として、ロール回転軸を多用し、像を得ていることが確認された。これは事前検討を裏付ける結果であった。来年度に開発を予定する二次試作機への改良点として、ロール回転ユニットの装着機構について、より容易に脱着を可能とするような改良が求められる。超音波画像については画像の向上が期待される。現在、新たなプローブを開発中であり、より高解像度になることを予定しており、よってこの点については改善の予定である。また、狭所においてはロボットの機構の一部と臓器が干渉する場面が見られた。臓器損傷などの事象は見られなかったが、今後の改良の参考にしたい。

Ｃ．結論

これら小項目による研究成果により、開発した一次試作機に関して適切な評価が得られ、本項目として掲げた平成２６年度開発目標を達成した。

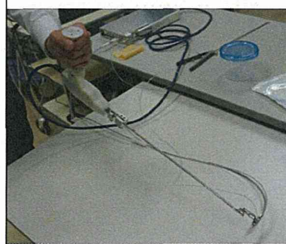
II. 委託業務成果報告（業務項目）

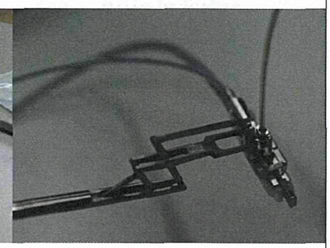
２．評価に関する研究

（資料）試作１号機ドライボックス動作評価

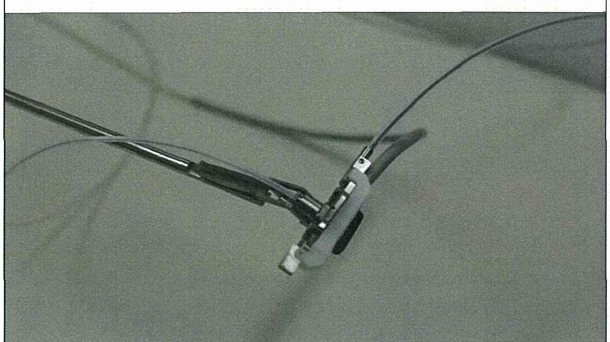
試作1号機ドライボックス動作評価

試作1号機によるドライ環境での動作評価を実施した

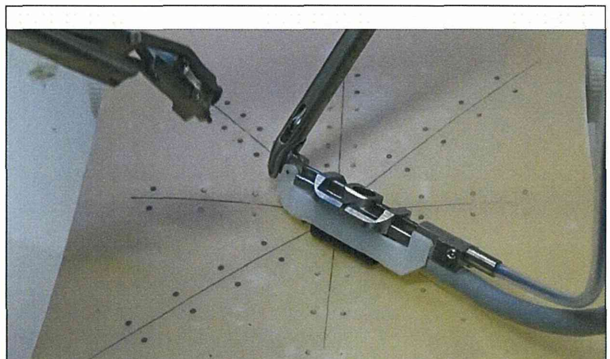




試作一号機外観



（参考）ロボット動作

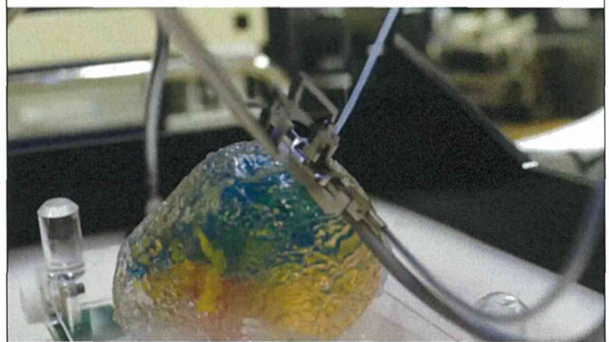


（参考）ドライボックスでの合体分離動作

ドライ評価環境

ヒト肝臓のCT画像より構築した，内部に音響特性の異なる血管構造を有し，超音波プローブでの画像取得可能なファントムを用いる

実験風景



動作評価

ファントムの血管位置の同定が可能であることを確認

II. 委託業務成果報告（業務項目）

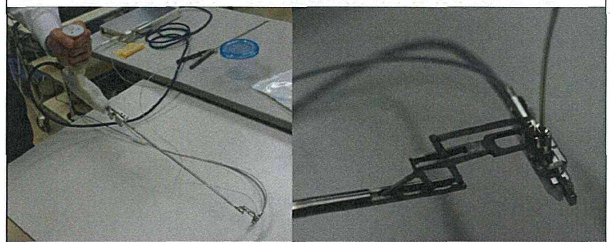
２．評価に関する研究

（資料）試作１号機動物実験報告

試作1号機動物実験報告

実験目的

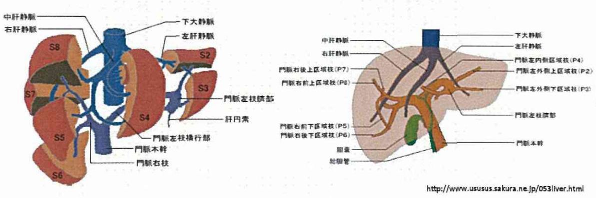
開発した試作機の有用性評価
および必要動作域の確認検討



試作一号機外観

実験方法

ブタ腹腔内にて試作1号機を用いて超音波画像から腫瘍等位置同定の基準となる複数の静脈を観察する走査を繰り返し実施する. このときの走査動作映像を記録し, 装置の有用性評価, および必要動作域の確認検討を行う.



http://www.ususus.sakura.ne.jp/053liver.html

ヒトの正常肝臓の解剖

内視鏡映像で見るロボット動作(1/2)

・最初にアプローチ角を決定した後, 主としてロール回転軸のみで走査する傾向が強い

内視鏡映像で見るロボット動作(2/2)

・この例ではアプローチ後, 微小な動作しか行わないが早期に静脈位置を同定できた

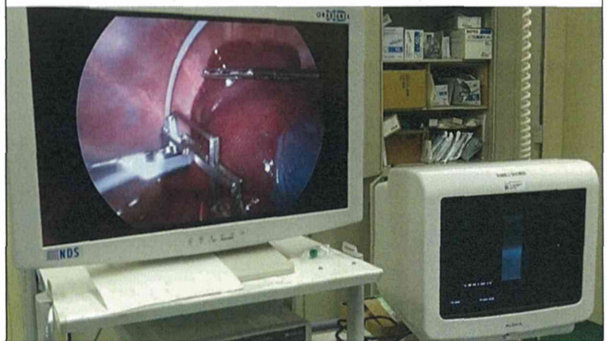
カメラ映像で見るロボット動作(1/3)

・走査による静脈位置を同定プロセスの一例

カメラ映像で見るロボット動作（2/3）

・別の例．アプローチ～走査～静脈の位置同定

カメラ映像で見るロボット動作（3/3）



・より狭所へのアプローチ例

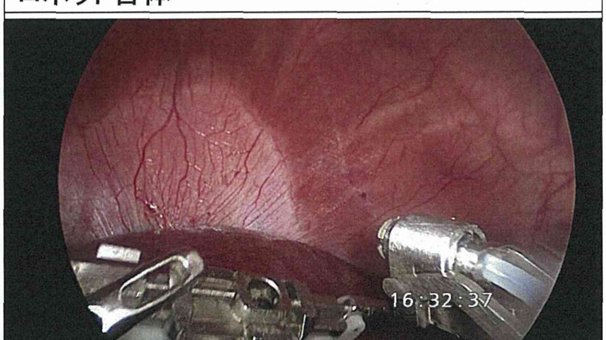
術者動作

・回転中心がプローブ面に存在するため，走査中は手首位置をほぼ固定して安定した走査を可能と出来た

US画像

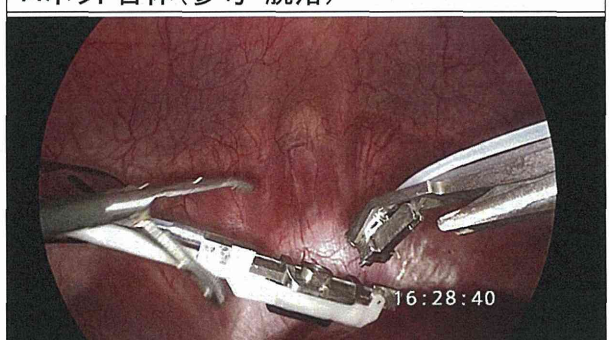
・安定した走査画像を得ることが出来た．画質は開発中の新型プローブにて改善の予定

ロボット合体



・ピン挿入の難度が高く，改良の必要性が確認された．

ロボット合体（参考・脱落）



・合体部の結合不良により脱落するケースが見られた

ロボット分離・取り出し

・分離はワンタッチのボタン操作で容易に可能であった

動物実験のまとめ

・回転中心機構により静脈探索を容易に実現できた
・術者はほぼ試作機を固定して安定した走査を実現できた
・これらのことから，装置の有用性が確認された
・動作域は十分である可能性．ロール軸の重要性が改めて確認
・狭所へのアクセスでは，一部に装置と臓器の干渉が見られる
・US画質は開発中の新プローブに期待
・腹腔内合体機構について改良検討

III. 学会等発表実績

学 会 等 発 表 実 績

委託業務題目「腹腔鏡下超音波検査を簡単操作に変える手首運動を再現した遠隔回転中心を有する多自由度自在電動アーム」
機関名　国立大学法人　九州大学

１．学会等における口頭・ポスター発表

発表した成果（発表題目、口頭・ポスター発表の別）	発表者氏名	発表した場所（学会等名）	発表した時期	国内・外の別
Multi-Degrees Of Freedom Laparoscopic Ultrasound Probe With Remote Center Of Motion	Susumu Oguri, Jumpei Arata, Tetsuo Ikeda, Ryu Nakadate, Shinya Onogi, Tomohiko Akahoshi, Kanako Harada, Mamoru Mitsuishi, Makoto Hashizume	Int J CARS	2015年6月予定	国外

２．学会誌・雑誌等における論文掲載

掲載した論文（発表題目）	発表者氏名	発表した場所（学会誌・雑誌等名）	発表した時期	国内・外の別
Articulated minimally invasive surgical instrument based on compliant mechanism	Jumpei Arata, Shinya Kogiso, Masamichi Sakaguchi, Ryu Nakadate, Susumu Oguri, Munenori Uemura, Cho Byunghyun, Tomohiko Akahoshi, Tetsuo Ikeda, Makoto Hashizume	Int J CARS	2015年1月	国外

Ⅳ．研究成果の刊行物・別刷

Int J CARS
DOI 10.1007/s11548-015-1159-4

ORIGINAL ARTICLE

Articulated minimally invasive surgical instrument based on compliant mechanism

Jumpei Arata · Shinya Kogiso · Masamichi Sakaguchi · Ryu Nakadate · Susumu Oguri · Munenori Uemura · Cho Byunghyun · Tomohiko Akahoshi · Tetsuo Ikeda · Makoto Hashizume

Received: 22 September 2014 / Accepted: 4 February 2015

Abstract
Purpose In minimally invasive surgery, instruments are inserted from the exterior of the patient's body into the surgical field inside the body through the minimum incision, resulting in limited visibility, accessibility, and dexterity. To address this problem, surgical instruments with articulated joints and multiple degrees of freedom have been developed. The articulations in currently available surgical instruments use mainly wire or link mechanisms. These mechanisms are generally robust and reliable, but the miniaturization of the mechanical parts required often results in problems with size, weight, durability, mechanical play, sterilization, and assembly costs.
Methods We thus introduced a compliant mechanism to a laparoscopic surgical instrument with multiple degrees of freedom at the tip. To show the feasibility of the concept, we developed a prototype with two degrees of freedom articulated surgical instruments that can perform the grasping and bending movements. The developed prototype is roughly the same size of the conventional laparoscopic instrument, within the diameter of 4 mm. The elastic parts were fabricated by Ni-Ti alloy and SK-85M, rigid parts ware fabricated by stainless steel, covered by 3D- printed ABS resin. The prototype was designed using iterative finite element method analysis, and has a minimal number of mechanical parts.
Results The prototype showed hysteresis in grasping movement presumably due to the friction; however, the prototype showed promising mechanical characteristics and was fully functional in two degrees of freedom. In addition, the prototype was capable to exert over 15 N grasping that is sufficient for the general laparoscopic procedure. The evaluation tests thus positively showed the concept of the proposed mechanism.
Conclusion The prototype showed promising characteristics in the given mechanical evaluation experiments. Use of a compliant mechanism such as in our prototype may contribute to the advancement of surgical instruments in terms of simplicity, size, weight, dexterity, and affordability.

Keywords Minimally invasive surgery · Articulated surgical instrument · Compliant mechanism · Robotic surgery

J. Arata (✉)
Department of Mechanical Engineering, Faculty of Engineering, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan
e-mail: jumpei@mech.kyushu-u.ac.jp

R. Nakadate · M. Hashizume
Center for Advanced Medical Innovation, Kyushu University, Fukuoka, Japan

S. Kogiso · M. Sakaguchi
Department of Engineering Physics, Electronics and Mechanics, Nagoya Institute of Technology, Nagoya, Japan

S. Oguri · M. Uemura · C. Byunghyun · T. Akahoshi · T. Ikeda
Department of Advanced Medical Initiatives, Faculty of Medical Sciences, Kyushu University, Fukuoka, Japan

Purpose

In minimally invasive surgery (MIS), instruments are inserted from the exterior of the patient's body into the surgical field inside the body through the minimum incision, resulting in limited visibility, accessibility, and dexterity. MIS minimizes the invasiveness of surgical procedures, but results in limited visibility, accessibility, and dexterity because of the limited view through the endoscope and the restricted movements of the surgical instruments. To address this problem, surgical instruments with articulated joints and multiple degrees of

Published online: 21 February 2015

freedom (DOF) have been developed and are commercially available.

The da Vinci system (Intuitive Surgical, USA) [1] is a well-known surgical robotic system that includes articulated robotic forceps and other instruments. This system provides good dexterity for the surgeon, but is expensive and requires a cumbersome preparation process including drastic changes to the operating room (OR) before deployment. Handheld robotic surgical instruments with articulated tips have also been developed, which are more compact and easier to deploy in the OR than the da Vinci system [2–5]. However, these devices are also complex and are more expensive than conventional surgical instruments. JAiMY (EndoControl, France) [2] is a commercially available laparoscopic handheld robotic instrument, which has a 5-mm-diameter tip and three DOF. KIMERAX (Terumo Europe, Belgium) [3,4] is another instrument with multiple DOF at the tip, which can be manipulated with a handheld controller. However, production of KIMERAX has been discontinued, and it is not available at the time of writing. Another example is DEX robot from Dextérité Surgical [5] that is equipped with the multiple DOF at the tip.

In addition to robotic surgical instruments, use of non-motorized articulated surgical instruments has been widely studied in several areas of surgery. Non-motorized articulated surgical instruments usually have levers or dials with a mechanical connection to the tip of the instrument, which are used to manipulate the tip. As these instruments are handheld and are not motorized, they are easy to deploy in the OR. Articulated instruments were introduced early in single-incision laparoscopic surgery [6–8], because surgery through a single incision restricts the ability to move the instruments, and movement with multiple DOF is important. A bendable needle holder for general laparoscopic surgery that has a series of bevel gears is commercially available from Tuebingen Scientific [9]. Mizuho produces forceps with a 3-mm- diameter bendable tip [12] for use in endoscopic sinus surgery [10] and pituitary surgery [11], and the Serpent forceps with a bendable tip produced by Entrigue Surgical [13] are also used in sinus surgery.

Laparo-Angle Articulating Instrument from Cambridge Endo [14] is equipped with a bending articulation at the tip, and rotation and grasping motions are also feasible. The device has been designed for single-incision laparoscopic surgery.

The articulated surgical instruments described above all have wire or link mechanisms. The general mechanical setup of laparoscopic surgical instruments has previously been described [15]. The mechanisms are generally robust and reliable, but the miniaturized mechanical parts required result in problems with the size, weight, durability, mechanical play, sterilization, and cost. To address these problems, we developed a compliant mechanism for use in articulated surgical instruments. Use of a compliant mechanism enables development of simple, compact, lightweight, dexterous, and affordable instruments. Compliant mechanisms [16–18] use one or more deformable elastic structures to transmit force, rather than using a conventional hinge joint. Compliant mechanisms have no backlash, do not need lubrication, are free from mechanical noise and abrasion powder, and are simple, compact, and lightweight because of their monolithic structure. Lange et al. [19] used a topology optimization process to develop an instrument with a compliant mechanism for use in MIS. Sato et al. [20] developed 1.4-mm-diameter microforceps with an elastic hinge. We have previously described a robotic manipulator that used a compliant mechanism [21].

The aim of this study is to investigate the feasibility of the use of compliant mechanism for multiple DOF surgical instrument. We thus developed with two DOF (grasping and bending) with compliant mechanism that has a relatively simpler configuration than other higher DOF instruments, to assess the feasibility of compliant mechanism in surgical instruments. Preliminary concept and prototype have been presented in authors' past publications [22,23]

Method

Mechanism design and prototype implementation

To assess the feasibility of using a compliant mechanism in surgical instruments, we developed the prototype shown in Fig. 1. The tip of the prototype has two DOF: grasping and bending. The user performs grasping movements by opening/closing the thumb and bending movements by sliding the middle finger. The handle was designed to allow the user to perform stable combined bending and grasping movements in an intuitive manner.

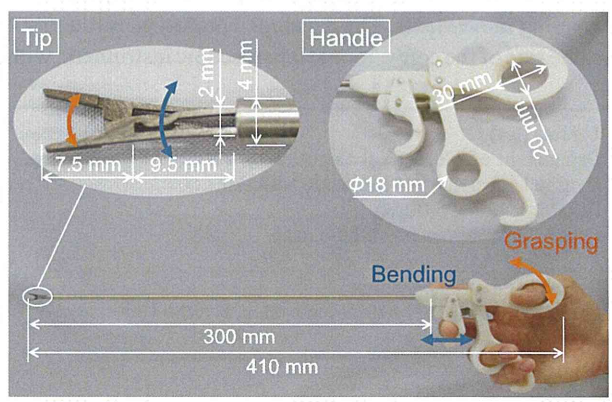


Fig. 1 Overview of the prototype. The tip has two DOF: bending (illustrated in *blue*) and grasping (illustrated in *red*). The force applied by the user's index finger and thumb is converted to the tip two DOF motion by the mechanism. Rotation around the long axis can be achieved by rotating the user's wrist

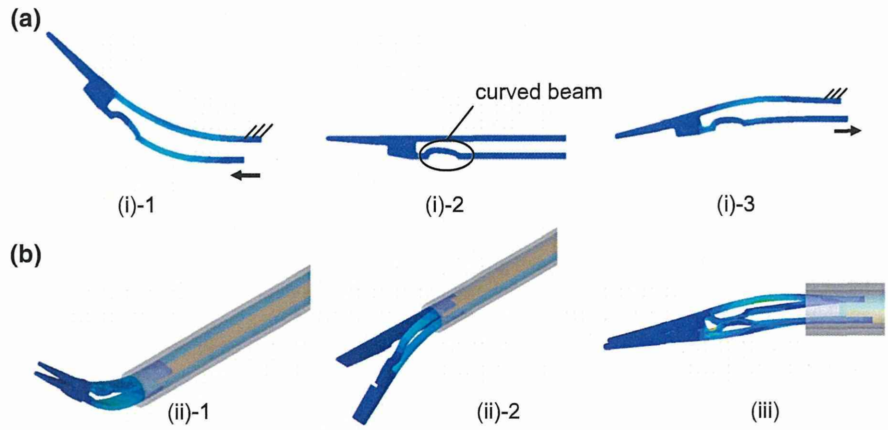


Fig. 2 FEM analysis of movement of the prototype. The color represents the distribution of stress. (i) FEM analysis of movement of a single blade. (ii) shows combined bending and grasping movements, and (iii) shows the effects of the curved beam during the grasping movement

The tip of the prototype consists of two spring blades that use a compliant mechanism to move. The prototype is 4 mm in diameter and 410 mm in length, and the other dimensions such as the size of the handle are the same as in conventional laparoscopic instruments. The dimensions of the blade were optimized by iterative finite element method (FEM) analysis using DAFUL Ver.3.4 (Virtual Motion, Inc.) [24]. The working range is ±45° for bending and ±60° for grasping, even when the movements are combined. Optimization was achieved based on a design trade-off between the dimensions (thickness and beam length) and the maximum stress within the working area (which should be less than material's range of elastic deformation). Topological optimization regarding compliant mechanism by computation is recently investigated [25]; however, it is known that the method is still under development and there still be the difficulties to deal with many three-dimensional design parameters and computation time. Thus we tool an empirical method to optimize the shape of the elastic elements. The authors have conducted the design of compliant structure in an empirical manner for a relatively simpler structure [26]. The method is basically an iterative calculation in varying the shape in considering the design trade-off between the dimensions and the maximum stress within the working area, also the resistance force for bending, and ease of prototype implementation. In addition, the resistance force due to elastic deformation of the spring blades was taken into account to ensure that the user can easily perform the movements. As the spring blades are attached to a transmission bar and connected to the handle mechanism, the force exerted by the user is transmitted directly to the tip. The spring blades, mechanical bars, and handle were manufactured using Ni-Ti, SK-85M, and ABS resin, respectively.

Figure 2 shows the results of FEM analysis for bending and grasping movements. One of the ends of the blade slides back and forth along the long axis, while the other end is fixed, resulting in a bending movement. The two blades are placed symmetrically side by side. The tip bends when the blades bend in the same direction and grasps when only one blade bends, while the other is fixed. A curved beam structure on the blade increases the grasping force by a local stress concentration effect, as shown in Fig. 2b(iii). The tip of the forceps consists of two spring blades and is therefore simpler than in traditional surgical instruments. The two spring blades are fixed to the end of a rigid link bar to transmit the force from the handle mechanism, as shown in Fig. 3.

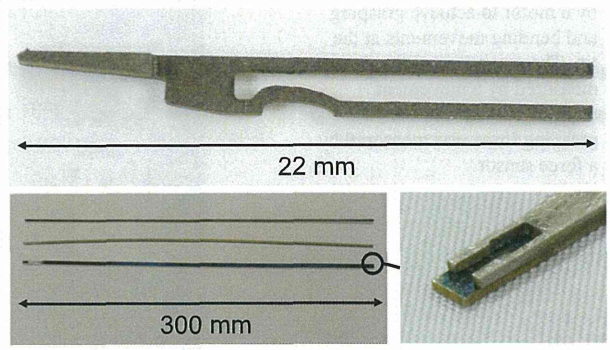


Fig. 3 *Upper panel* shows the fabricated spring blade. Two spring blades are fixed to the end of a rigid link bar to transmit the force from the handle mechanism, as shown in the *lower panels*

The handle mechanism was designed based on the conventional handles of laparoscopic surgical instruments. The surgeon thus can achieve the bending motion with the thumb, and the grasping motion with the index finger like as a trigger, in a way not much different from conventional surgical tools. To adequately transmit the driving force from the handle to the tip mechanism, each of the two spring blades is attached to the blue bar as shown in Fig. 4, to enable the bending movement. The other end of one spring blade is attached to the orange bar, while another is fixed to the sheath enabling the bending movement of a single spring blade for the grasping movement. The mechanism thus performs the two DOF bending and grasping motion.

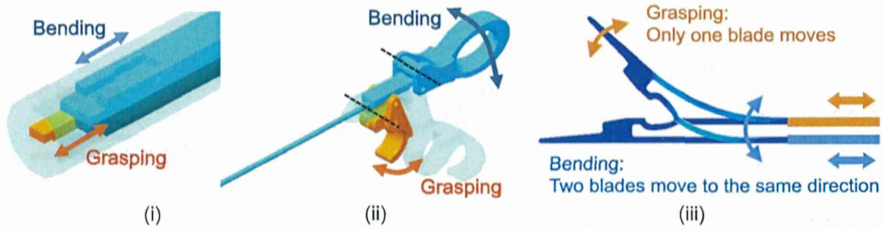


Fig. 4 (i) and (ii) show the bending and grasping movements that are transmitted to the tip independently as two linear movements of orange and *blue bars*. Tip mechanism consists of two spring blades. One end of each spring blade is attached to the *blue bar* for the bending movement. The other end of one spring blade is attached to the *orange bar*, while another is fixed to the sheath [shown as the *gray part* in (iii)] enabling the bending movement of a single spring blade for the grasping movement. The mechanism thus performs the two DOF bending and grasping movement

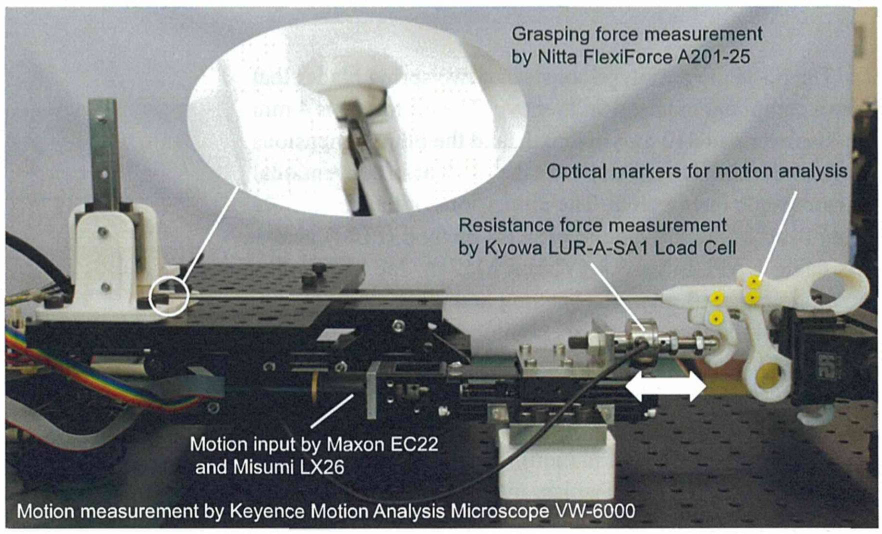


Fig. 5 With the prototype fixed to a rig, the handle was moved by a motor to achieve grasping and bending movements at the tip. The movement at the tip was measured by a movement analysis camera and the grasping force was measured by a force sensor

Experimental setup for mechanical evaluation

To show the feasibility of the use of compliant mechanism in surgical instruments with multiple DOF, we tested the mechanical characteristics of the developed prototype.

To test the grasping and bending motion, we developed the experimental setup shown in Fig. 5. The prototype was fixed to a rig, and grasping and bending movements were initiated by a linear motor that moved the handle. The movements of the tip were measured using a movement analysis camera, and the grasping forces were measured using a force sensor.

In the experimental setup, movements can be measured at the handle and the tip during grasping and bending. To measure the movement, the handle was moved using a linear motor (EC22, Maxon Co., Ltd.) with a ball screw and linear guide (LX26, Misumi Co., Ltd.). The movements at the tip were then measured using a movement analysis microscope (VW-6000, Keyence Co., Ltd.). In addition, the resistance force can be measured using a load cell (LUR-A-SA1, Kyowa Electronic Instruments Co., Ltd.) attached to the handle. To measure the force of the grasping movement, the handle was moved by the motor as described above, and the grasping force was measured using a force sensor (FlexiForce A201-25, Nitta Co., Ltd., Japan). As the force sensor used in this test was originally a pressure sensor, we performed a pre-calibration test to determine the relationship between the output and the actual grasping force on the prototype.

Results

Grasping movement

We conducted 10 times of repetitive trials in each measurement, resulted in similar tendency. We thus show the representative result for each measurement in this section. Figure 6 shows the grasping movement measurements. The vertical axis shows the grasping angle at the tip and the horizontal axis shows the linear movement of the handle by the linear motor. The blue line shows the pre-computed FEM analysis.

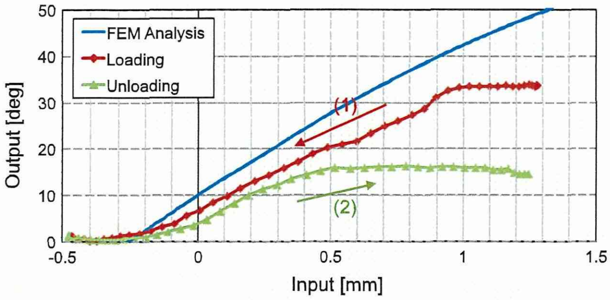


Fig. 6 Grasping movement measurements. The *blue line* shows the pre-computed FEM analysis. The results shows hysteresis between the handle and tip movements due to friction

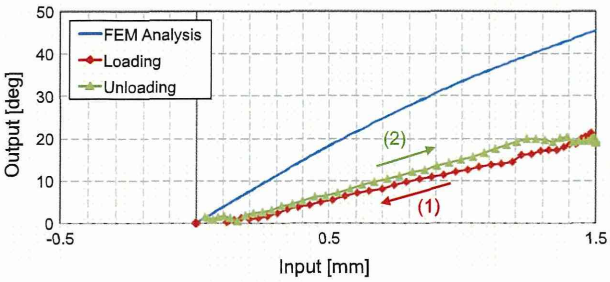


Fig. 7 Bending movement measurements. The *blue line* shows the pre-computed FEM analysis. The results do not show hysteresis or mechanical play between the handle and tip movements

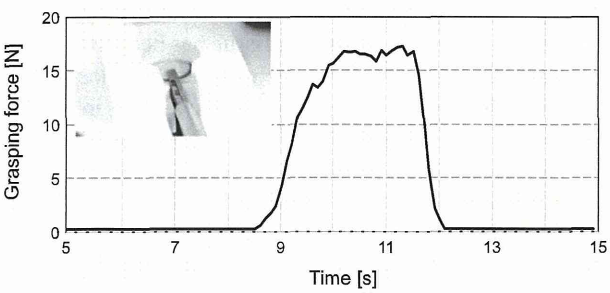


Fig. 8 Prototype achieved a grasping force of 15 N, which is sufficient for general laparoscopic surgical procedures

Bending movement

Figure 7 shows the bending movement measurements. The vertical axis shows the bending angle at the tip and the horizontal axis shows the movement at the handle. The results differ from the pre-computed FEM analysis, in a similar manner to the grasping movement results. No hysteresis or mechanical play was observed. The maximum resistance force observed at the handle during movement was 13.5 N.

Grasping force

Grasping test showed that the device is able to output more than 15 N of grasping force was achieved as shown in Fig. 8.

Conclusions

Based on the concept of improving the simplicity, size, weight, dexterity, and affordability of minimally invasive surgical instruments, we developed an MIS tool that uses a compliant mechanism. This paper described our prototype and its preliminary evaluation. The evaluation showed that use of our prototype is feasible. However, to further improve the design, the assessments regarding the discordance between FEM and measurement, and hysteresis are needed.

As shown in Sects. 3.1 and 3.2, the measured grasping angle did not reach the pre-computed angle because the FEM analysis did not consider friction within the instrument into account. Although no mechanical play was observed, the grasping angle did not recover to the initial angle, presumably because of friction. The grasping movement is converted to linear movement at the handle over a range of approximately 1.5 mm because of the limited space at the handle. In addition, only one spring blade bends during the grasping movement, resulting in friction between the rigid link bars. These two factors that have not been taken into account in FEM analysis, may have resulted in enough friction to cause hysteresis. In our compliant mechanism, the elastic elements are not bending alone but together with all other elastic and (ideally) rigid elements. For example, we determined the power transmission link as a rigid material in FEM analysis for the ease of computation; however, the link is supposedly deformed slightly then the friction occurs against the sheath. Errors in manufacturing would be also involved to the friction. The rigorous simulation of whole mechanism model would be difficult due to the analytical accuracy and computational time. We thus used the FEM analysis for design optimization then developed the prototype to conducted the mechanical evaluation to assess the feasibility. As the mechanism showed that it is fully functional, the feasibility of the mechanism was positively shown.

Although the motion tests regarding bending and grasping were independently conducted, these motions could be performed simultaneously because the two motions are essentially performed by the same deformation (Single spring blade deforms in grasping, and both spring blades deform in bending in the same manner). These motions are performed in the preliminary task without particular effort by the user. In addition, although no mechanical play was observed, the grasping angle did not recover to the initial angle, presumably because of friction. The grasping movement is converted to linear movement at the handle over a range of approximately 1.5 mm because of the limited space at the handle. In addition, only one spring blade bends during the grasping movement, resulting in friction between the rigid link bars. These two factors that have not been taken into account in FEM analysis may have resulted in enough friction to cause hysteresis.

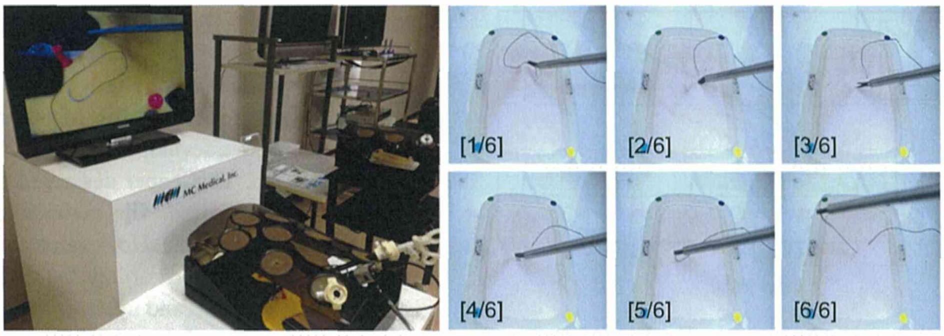


Fig. 9 Setup of the training box task (*left panel*) and a series of photographs taken during the suturing task (*right panel*)

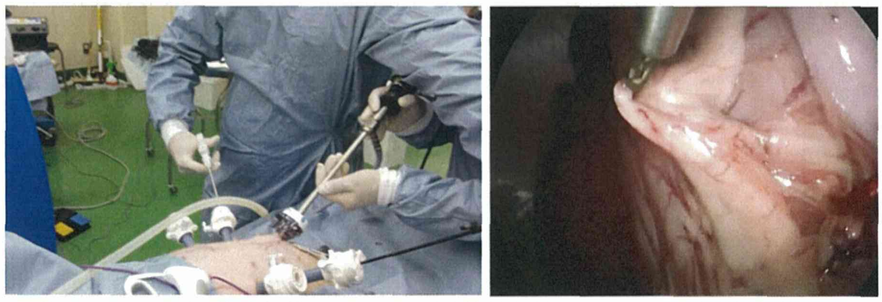


Fig. 10 Setup of the in vivo experiment (*left panel*) and view through the endoscope (*right panel*). The bending movement was used to apply appropriate traction to the tissues during the procedure

As a preliminary test for the utility test of the prototype, we performed a suturing task using a laparoscopic training box, and an in vivo test was performed in a pig. Figure 9 shows the setup of the suturing task performed using the training box, which was completed without any particular difficulties. The bending movement was used to insert the needle, and the grasping movement was used to grasp the tip of the needle after it had pierced the membrane. Figure 10 shows the experimental setup and the view through the endoscope at the in vivo test on a pig. The surgeon used the instrument with his right hand during the laparoscopic procedure. As shown in the right panel of Fig. 10, the bending movement was used to apply appropriate traction to the tissues during the procedure. No particular vibration caused by the mechanism characteristics observed during the test. Although the test showed that the prototype is fully functional, the performed test is preliminary and thus requires a further evaluation tests (e.g., statistical analysis in comparison with standard instruments) to evaluate the usability.

Our prototype is simple, small, lightweight, low-cost, and simple structure supposedly increases the ease of sterilization compared with conventional articulated MIS instruments. On the other hand, there is a drawback in the compliant mechanism shown in the experiment. The maximum resistance force observed at the handle during movement was 12 N, which is higher than in conventional articulated surgical instruments. In addition, 34 N of motor output was needed to exert 15 N of grasping as shown in Fig. 8. The main reason of the resistance force is the compliance of the mechanism. In the proposed mechanism, the mechanism deforms the structure for the power transmission, and thus the efficiency of the mechanism is relatively lower than the conventional link mechanisms. This issue has been discussed in [16] as "Because compliant mechanisms have elastic members that deflect, energy is stored in the system in the form of strain energy. Thus the energy available at the output may be considerably less than was provided at the input. This energy is not lost, but is stored and released later." In the proposed mechanism, the stored energy acts as the reaction force to deform the spring back to the initial shape (as shown in upper panel in Fig. 3).

It should be noted that the issue regarding the resistance force is also coupled with the mechanical configurations of pivots at the tip and handle. Applying an improved mechanical leverage to the handle may decrease the resistance force. However, the modification should be made in considering the usability, since the displacement will be generally increased due to the mechanical leverage. As described above, a further usability test is required to assess this issue. Note that the resistance force can be also decreased by a further optimization of the structure if it is needed (e.g., changing the spring blade to a softer material).

Use of a compliant mechanism such as in our prototype may contribute to the advancement of surgical instruments (e.g., the bending DOF would be useful at the narrow surgical area to increase the dexterity). We are currently working on further optimization of the spring blade design, and of the handle to improve usability and dexterity. The usability of the device will be tested further in complex surgical tasks such as suturing.

Conflict of interest Jumpei Arata, Shinya Kogiso, Masamichi Sakaguchi, Ryu Nakadate, Susumu Oguri, Munenori Uemura, Cho Byunghyun, Tomohiko Akahoshi, Tetsuo Ikeda and Makoto Hashizume declare that they have no conflict of interest.

Human participants and/or animals This article does not contain any studies with human participants performed by any of the authors. All procedures performed in studies involving animals were in accordance with the ethical standards of the institution or practice at which the studies were conducted.

References

1. http://www.intuitivesurgical.com (2014)
2. http://www.endocontrol-medical.com/jaimy.php (2014)
3. http://www.kymerax.com (2014)
4. Miniati R, Dori F, Cecconi G, Frosini F, Sacca F, Gentili BG, Petrucci F, Franchi S, Gusinu R (2014) Hospital based economic assessment of robotic surgery. IFMBE Proc 41:1144–1146
5. http://www.dexteritesurgical.com/dexteritesurgical-en/dex-robot (2014)
6. Romanelli JR, Earle DB (2009) Single-port laparoscopic surgery: an overview. Surg Endosc 23:1419–1427
7. Tacchino R, Greco F, Matera D (2009) Single-incision laparoscopic cholecystectomy: surgery without a visible scar. Surg Endosc 23:896–899
8. http://surgical.covidien.com/products/single-incision-laparoscopic-surgery/sils-stitch (2014)
9. http://www.tuebingen-scientific.com (2014)
10. Stammberger H, Posawetz W (1990) Functional endoscopic sinus surgery. Eur Arch Otohinolaryngol 247:63–76
11. Jho HD (1999) Endoscopic pituitary surgery. Pituitary 2:139–154
12. http://www.mizuho.co.jp/pnet/neurosurgery/neurosurgery-other/fcf/index.html (2014)
13. http://www.entriguesurgical.com/home/outside_US_products/serpent (2014)
14. http://www.cambridgeendo.com/products (2014)
15. Lim JJB, Erdman AG (2003) A review of mechanism used in laparoscopic surgical instruments. Mech Mach Theory 38:1133–1147
16. Howell LL (2001) Compliant mechanisms. Wiley-Interscience. ISBN 978-0-471-38478-6
17. Smith ST (2000) Flexures elements of elastic mechanisms. CRC Press. ISBN 90-5699-261-9
18. Lobontiu N (2002) Compliant mechanisms. CRC Press. ISBN 978-0-8493-1367-7
19. Lange D, Langelaar MN, Herder JL (2008) Towards the design of a statically balanced compliant laparoscopic grasper using topology optimization. In: Proceedings of ASME 2008 international design engineering technical conferences and computers and information in engineering conference (IDETC/CIE2008), pp 293–305
20. Sato R, Nokata M (2011) Development of one part grasping forceps for vascular catheter. J JSCAS 13(3):300–301 (in Japanese)
21. Arata J, Saito Y, Fujimoto H (2010) Outer shell type 2 DOF bending manipulator using spring-link mechanism for medical applications. In: Proceedings of international conference robotics and automation, pp 1041–1046
22. Arata J, Kogiso S (2013) Monolithically designed minimally invasive surgical tool using compliant mechanism. Int J CARS Suppl 1:S369–371
23. Arata J, Kogiso S, Sakaguchi M, Nakadate R, Oguri S, Uemura M, Cho B, Akahoshi T, Ikeda T, Hashizume M (2014) Articulated minimally invasive surgical tool for laparoscopy based on compliant mechanism. Int J CARS 9(Suppl 1):S183–184
24. http://www.virtualmotion.co.kr (2014)
25. Tolou N, Herder JL (2008) Towards the design of a statically balanced compliant laparoscopic grasper using topology optimization. In: International design engineering technical conference and computers and information in engineering conference, pp 1–13
26. Kozuka H, Arata J, Okuda K, Onaga A, Ohno M, Sano A, Fujimoto H (2012) Compliant-parallel mechanism for high precision machine with a wide range of working area. In: Proceedings of international conference on intelligent robots and systems, pp 2519–2524

#203 - Lecture or Poster

Multi-Degrees Of Freedom Laparoscopic Ultrasound Probe With Remote Center Of Motion

Science, Informatics and Engineering in Healthcare / Biomedical Engineering / Medical robotics and manipulators

Susumu Oguri[1], **Jumpei Arata**[1], Tetsuo Ikeda[1], Ryu Nakadate[1], Shinya Onogi[1], Tomohiko Akahoshi[1], Kanako Harada[2], Mamoru Mitsuishi[2], Makoto Hashizume[1]

1. Kyushu University, Fukuoka, Japan
2. Tokyo University, Tokyo, Japan

keywords:Ultrasound Probe, Laparoscopy, Remote Center Of Motion, Surgical Robot

Purpose: In digestive surgery, endoscopic surgery has been widely introduced because of its minimally invasiveness. On the other hand, high technical skills for surgeons are required because the movements of the thin and long surgical instruments for minimally invasive surgery are limited compared to those for conventional surgery. Image guidance is one of the key technologies to ensure the safety in minimally invasive surgery, however, conventional navigation systems are not effective in digestive surgery due to the large deformations and movements of the organs and surrounding tissues. Thus, the safety largely depends on the individual surgeon's skills [1].
To tackle this problem, we are currently developing a laparoscopic ultrasound probe with multi-Degrees Of Freedom (DOF). There is a commercial multi-DOF ultrasound probe (UST-5418, Hitachi-Aloka Medical, Japan), however, the design of the probe motion cannot enable the ultrasound probing while keeping the contact point (Fig. 1). Therefore, we designed a 3 DOF mechanism with its Remote Center of Motion (RCM) located at the organ's contact point to enable the ultrasound probing that is similar to the conventional US probing on the body surface. The robotically supported precise ultrasound scan in laparoscopic digestive surgery would be beneficial for various purposes including the real-time diagnoses of the tumor infiltration, the structures of blood vessels surrounding the tumor, and lymph node metastases. The goal of the study is to develop the multi-DOF laparoscopic ultrasound probe which can be easily employed in the conventional laparoscopic surgery.

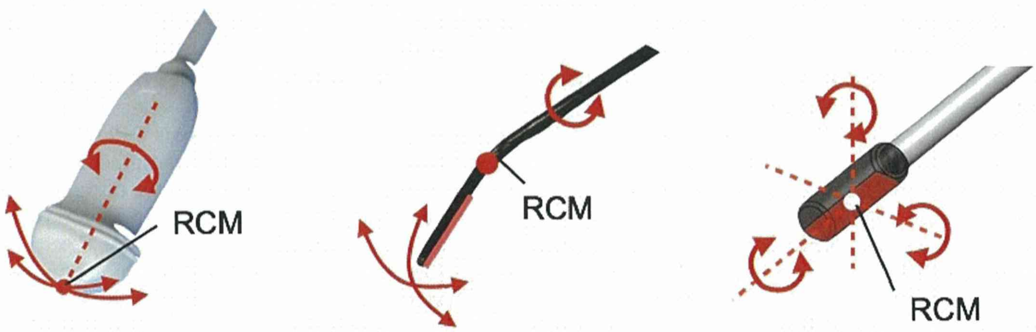
Methods: The proposed system consists of a hand-held device and a navigation system. The navigation system reconstructs 3D image using 2D ultrasound images by obtaining the probe's position using 3D positioning sensors attached to the device. The reconstructed image will be overlaid on the endoscopic image to identify the location of the tumor and surrounding blood vessel network. In this paper, the concept and the prototype of the hand-held device are described and discussed.
The hand-held device consists of a grip with actuators, a 2 DOF unit and an ultrasound probe attached to a 1 DOF mechanism (shown in Fig.2). An external control unit that contains motor drivers and volume switches for speed control is connected to the device by signal and power cables. The 2 DOF unit is directly attached to the grip and enables the 2 DOF rotational motions at the tip (Pitch and Yaw). The parallelogram mechanism attached to the tip enables the pitch motion with the RCM located on the surface of the ultrasound probe. The rotation about the device's long axis enables the yaw motion. Note that the device's long axis is shifted by 3 mm from the grip's axis so that the center of rotation corresponds to the RCM. The ultrasound probe is attached to the 1 DOF mechanism for the roll motion, and the mechanism is driven by a flexible shaft. Therefore, the 3 DOF device with the same RCM can perform an ideal scanning motion.
The length of the shaft is 420 mm, and its diameter is 5 mm. The range of motion is ±45° for the pitch and yaw motions, and ±180° for the roll motion. Note that the motion ranges may vary in the next prototypes. The shaft of the device and the ultrasound probe with the 1 DOF mechanism will be separately inserted to the abdominal cavity from two different trocars in clinical practices. The ultrasound probe and the shaft can be easily assembled/disassembled using the mechanical notches implemented on both sides. One of the advantages of the intracorporeal assembly is that the ultrasound probe with the flexible shaft is sufficiently small to accommodate another surgical instrument in the same trocar. The parallelogram mechanism can be folded down to the size of 7.5 mm in diameter and thus can be inserted through a 12 mm trocar.
The prototype used a compact sterilizable probe UST-533 (Hitachi-Aloka Medical Co., ltd., Japan) of approximately 9 mm in diameter and 15 mm in length. The motions of the 2 DOF unit are driven by the DC servomotors and linear actuator units (Maxon RE8+MR+GP8A) implemented in the grip. The motor for the roll motion is implemented in the external control unit, and the motion is transmitted by a flexible shaft to the 1 DOF mechanism. The grip was fabricated by a 3D printer (Eden 350 V, Objet Geometries Inc., USA) and has an ergonomic shape to provide a stable holding of the device during the procedure. Six buttons of the grip provide the control of 3 DOF (based on the ON-OFF control, and the motion speed can be tuned from

0 to 1 rotation par second by using mechanical volume switches). Total weight of the prototype device is 370 g. The 2 DOF unit and the ultrasound probe can be separated from the device for sterilization.

Results: We conducted a preliminary ultrasound scan using a liver phantom that contained a dummy tumor and blood vessels with different acoustic characteristics. The phantom was fabricated using CT data and a silicon rubber with the approximately same hardness as the human liver was used. The scan test was conducted by an experienced surgeon. Note that the test was conducted without the navigation system, and the prototype device and a conventional ultrasonograph (Prosound Alpha-7, Hitachi-Aloka Medical Co., ltd., Japan) were used. In the experiment, the surgeon successfully located the tumor and its surrounding blood vessels. Thus, the feasibility of the device was demonstrated.

Conclusions: In this study, we proposed a multi-DOF laparoscopic ultrasound probe that can keep the RCM on the organ's surface. The concept, prototype implementation and preliminary evaluation were reported in the paper. The test showed a promising result for efficient real-time ultrasound diagnosis. The robotic precise ultrasound scan in laparoscopy would be beneficial for various purposes. In addition, as the ultrasound scanning is non-invasive and the image can be obtained in real-time, the proposed device would increase the safety and outcome in the general laparoscopic surgery. We are currently planning to conduct an in-vivo test on pig to verify the feasibility of the prototype.

References: [1] Nicolau S, Soler L, Mutter D, Marescaux J (2011) Augmented reality in laparoscopic surgical oncology, Surgical Oncology, 20:189-201.
[2] Konishi K, Nakamoto M, Kakeji Y, Tanoue K, Kawanaka H, Yamaguchi S, Ieiri S, Sato Y, Maehara Y, Tamura S, Hashizume M (2007) A real-time navigation system for laparoscopic surgery based on three-dimensional ultrasound using magneto-optic hybrid tracking configuration, Int J CARS 2:1–10.



(a) Ideal US scan outside the body: the probe moves centered to the interest area

(b) Conventional laparoscopic US probe largely moves thus difficult to stay in the interest area

(c) Proposed device enables the 3 DOF desirable motion as (a) in the abdominal cavity