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A body-mounted surgical assistance robot for minimally invasive spinal puncture surgery

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Abstract— **Robotic surgical assistant systems can transcend the precision of surgical procedure by integrating the position information of patient and robot in the surgical room. There are two conventional integration methods, the real-time position tracking and physically fixing. In clinical cases, the former has the problem of increasing radiation exposure; so physical fixation is more commonly used in robotic surgery. However, the conventional fixing methods are also not optimized and problems of invasiveness and rigidness of fixation are left unsolved.**

This paper deals with a body-mounted surgical assistance robotic system for percutaneous vertebroplasty. The robot is fixed on the human body surface by fixing device that utilizes jamming transition phenomenon and vacuum cup. The body-mounted robot system sets up the correct pathway for needle insertion. The system was fixed on human shape target with a 166±8 N suction force. The fixing rigidity of our system and accuracy of the needle guide control device has been evaluated by measuring the displacement during needle inserting operation. The displacement of the fixing device by the external force of needle inserting operation was 0.06 mm and 0.02° in RMS. The total displacement of needle guide was 1.66 mm and 1.24° in RMS. The total positioning error of the needle guide control device was 0.09 mm and 0.97° in RMS.

I. Introduction

Robotic surgical assistant system is one way to improve surgical accuracy and safety by minimizing error in surgery. Robotic surgical assistant systems need to have knowledge of the geometrical position of patient's affected area in order to work precisely and accurately. The data of patients and robots is measured by medical modality. The two coordinate systems are integrated to find an initial relationship. When this relationship changes involuntarily, the robotic surgical assistant systems could not perform correct surgical operation. Therefore, the geometrical relationship between patient and robot should be tracked in real-time or be physically fixed. As the former method, X-ray serial radiography [1] is one of the straightforward ways to achieve continuous acquisition of position and orientation of a diseased part inside of the body. Though, taking X-ray images for the full-time of surgery cannot be recommended because of the exposed dose of radian. In clinical cases, the geometrical relationship between patient and robot should be fixed rigidly to eliminate the need for retaking X-ray images during surgery. The fixing capability directly relates to the accuracy of robotically surgical assistant system. But, the method of fixation has not been optimized until now. The common fixing method in clinical practice is the invasive fixation with bone insertion pins or screws. Shoham *et al.* [2] developed a bone-mounted robot for spine puncture surgery. This robot is fixed on the bone around the affected area by inserting fixing pin into the bone. The positioning accuracy of this needle guiding mechanism is better than 0.1 mm. This system ensures strong fixing and correct positioning of the needle. But, it is less than optimal in terms of the additional invasiveness needed for fixation. As a way to minimize invasiveness, Walsh *et al.* [3] and Maurin *et al.* [4] developed small surgical robots that are mounted on the patient's body surface with a belt. This method introduces no additional invasiveness for the patient, but relationship shift between patient and robot is likely to occur because the belt fixation is vulnerable to unidirectional external forces. To solve the fixation problems as described previously, no-invasive and rigid fixation is ideally required for robotic surgical assistant system. In this paper, we propose a novel fixing method that meets the requirements.

Percutaneous vertebroplasty is one example of spine puncture surgery that requires the high accuracy of robotic surgical assistant systems because pedicle screw insertion requires positioning a screw in the correct position while avoiding damage to the surrounding delicate area such as spine nerve [5]. The surgery needs to satisfy the acceptable accuracy of 3 mm and 3°, and achieve the ideal accuracy of 1 mm and 1° for screw insertion. The accuracy of 2D-3D registration for spinal surgery is presented by Russakoff *et al.* [6] and the mean target registration error was 1.3 ~ 1.5 mm. The accurate registration result should be reflected in spine surgery by using surgical assistance robot. We designed a body-mounted surgical assistance robot that is fixed onto a patient without increasing invasiveness. To enhance the posture stability of the robot on the patient's back, the center of gravity should be set low. Furthermore, the device has to ensure the region for X-ray view during the surgical operation and the sterilization of the parts that directly contact with tools needs to be done easily.

The proposed fixing device is used to fix the robot onto patient's body surface. The human back is uneven and the characteristic of it depends on the individual bony framework around the affected area. The major candidate for spine surgical treatment is the lumbar spine and the human back around this area is concave. The fixing device has to hold the

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patient's body surface in close relation and keep the geometrical relationship between surgical robot and affected area of the patient rigidly. The proposed device can fit to various patient body shapes and becomes hardened by using jamming transition phenomenon.

II. METHODS

A body-mounted surgical assistance robot system is shown in Fig. 1. The system consists of the fixing device and the needle guiding mechanism.

A. Fixing device

The fixing device deforms freely to conform to the surface of a target, and can transition to solid-like state to maintain the deformed shape. This function is controlled by the jamming transition phenomenon. This phenomenon is a phase transition from fluid-like to solid-like condition of the particle system. The phenomenon is controlled by increasing the density of particles. As an example of this phenomenon, Amend *et al.* [7] has reported a universal robotic gripper that catches hold of a target by using jamming transition of granular powders. We propose a medical fixing device that uses an elastic container made from silicon rubber cloth and odd shaped particles to make the stiffness-controlled pad using the jamming transition phenomenon. The vacuum system is connected to the container and the density of particles is controlled by the vacuuming air in the pad. In our system, first, we press the elastic container that is filled with fluid-condition particles against the patient's back, and the contour of the container and the particle system is deformed and holds the surface of the patient's back. After that, by vacuuming the air in the container, the density of particle system is increased and the phase changes to the solid-state. After the change in phase, the elastic container retains the shape of the target. A space is made at the center part of the container, and the system works as a vacuum cup by evacuating the air from this area to achieve strong fixation (Fig. 2).

B. Needle guiding mechanism

The overview of the needle guide control device is shown in Fig. 3. The needle guide control device consists of 2 DOFs for the orientation control part (Fig.3 (a)) and 2 DOFs for the position control part (Fig.3 (b)). We used spherical coordinate system consists of two crossing curved guides to build the orientation control part. The needle guide is set to the intersection of the two curved guides, and the orientation of the needle guide is determined as the intersection of the two curved guides by rotating α and β axes. These axes are coplanar and the intersection of the two axes is a mechanical pivot point for the needle guide. The position of the needle guide is determined as the motion in a polar coordinate system by using 1 DOF translation of t axis and 1 DOF rotation of θ axis. The orientation of needle guide is described as

$$\vec{l} = \left(-\sin\alpha\cos\beta, \cos\alpha\sin\beta, \sin\alpha\sin\beta\right). \quad (1)$$

The position of mechanical pivot point is described as

$$\vec{p} = \left(t\sin\theta, t\cos\theta, 0\right). \quad (2)$$

The path of the needle is described as (3) by using an intervening variable n

$$\vec{L} = \vec{p} + n\vec{l} = \left(t\sin\theta - n\sin\alpha\cos\beta, t\cos\theta + n\cos\alpha\sin\beta, n\sin\alpha\sin\beta\right). \quad (3)$$

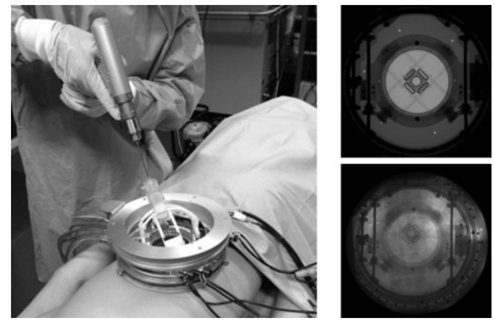

Figure 1. A body-mounted surgical assistance robot system and the X-ray photograph of the device and spine.

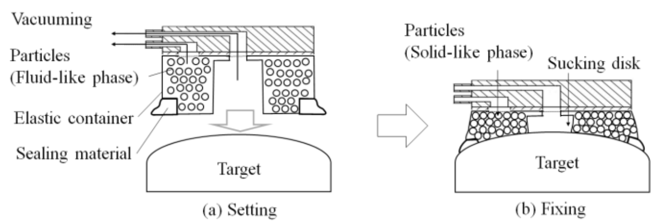

Figure 2. The mechanism of the vacuum system using jamming transition.

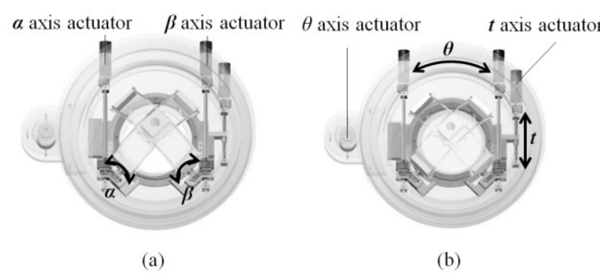

Figure 3. Concept of the orientation and position control of needle guide. (a) Orientation control and (b) position control.

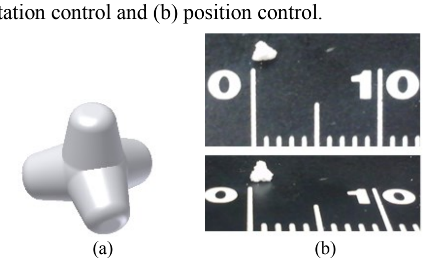

Figure 4. The tetra-pod shaped particle. (a) Design and (b) actual particle.

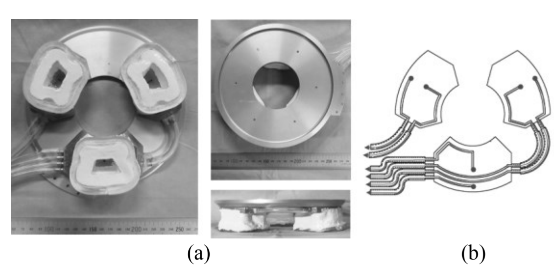

Figure 5. Overview of (a) the fixing device and (b) the suction ports and air pathways for the jamming transition and body surface fixing.

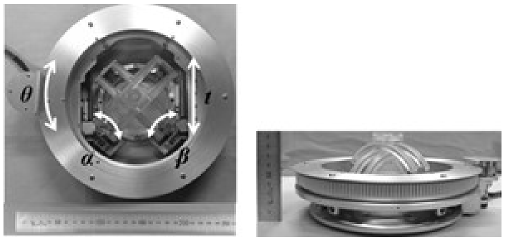

Figure 6. The overview of the needle guide control device.

C. *Implementation*

The fixing device was composed of particles that is used for jamming transition and elastic container that works as a vacuum cup. The particle shape and size have an effect on the jamming transition phenomenon, and the shape strongly affects the stiffness of the jammed particle system. When the shape of a particle is a sphere, the rigidness of particle system is not strong, even after the jamming transition has occurred. The particle should be oddly shaped to prevent the turning in orientation and shifting in the location of the particles. We fabricated tetra-pod shaped particles of gypseous material (zp150, 3D Systems) by the 3D printer (ZPrinter450, 3D Systems) to ingenerate the rigidity of the particles arrangement when jamming transition occurs (Fig. 4).

The arrangement of the fixed point and the size of the device was determined on the basis of the human body dimensions and shape model that was published by Kawauchi *et al.* [8]. We designed a tripod-fixing device that avoids large irregularity while stably fixed on the object. The height of vacuum cup was 20 mm and the thickness of the body was 10 mm. The bottom area that contacts with a target was 5.2×10^3 mm^2 (Fig. 5). The area of a suction pad S [mm^2] was 7.0×10^3 mm^2, and 3 pads worked to fix the robot onto the target. When the vacuum pressure inside of the suction pad is P [MPa], the fixing force W [N] is

$$W = PS. \qquad (4)$$

The vacuum system was composed of an air compressor (CP-100, NAKATOMI Co., Ltd.) and a vacuum generator (VBH07-66P, PISCO Co., Ltd.). Considering the negative pressure in clinical case, the stabilizer for coronary artery bypass graft uses about –50 kPa for heart surface, and the vacuum extraction cup for delivery needs –60 kPa or more. The suction application for discharge uses about –20 kPa with protecting mucosal. According to these precedents, we set a negative pressure inside of the suction pad at –20 ~ –30 kPa for clinical application. To control the vacuum pressure inside of the suction pad, vacuum regulator (RVV6UG, PISCO Co., Ltd.) was connected between the vacuum generator and vacuum ports in the suction pad. We fabricated the elastic container with 0.5 mm thickness silicon rubber cloth. It has enough flexibility and the compressive elastic modulus of the silicon rubber (KE-12, Shin-Etsu Chemical Co., Ltd.) is 0.3 MPa. The sealing gel that surrounds the external frame of suction pad was a non-viscous gel seat (CRG-N0505, TANAC Co., Ltd.) that has over 1300% degree of extensibility.

The overview of the needle guide control device is shown in Fig. 6. Actuators for α and β axes were separated from the curved guides, so the orientation control part and needle guide which directly contact with tools were detachable. 45 degrees bevel gears were applied to transmit the rotation of the actuator to α and β axes. The actuators of α, β, t axes were located at the bottom of the needle guiding mechanism with same directions. A hole of 70 mm in diameter was made at the center of the position control part. Currently, curved guides and needle guide were fabricated with acrylic resin (VeroClear, Stratasys Ltd.) by 3D printer (Objet CONNEX 500, Stratasys Ltd.). Other parts of the needle guiding mechanism were fabricated with stainless steel and aluminum alloy. The width of the needle guide control device was 220 × 253 mm and the height was 95 mm. The weight was 1963 g. The driving ranges of orientation and position control were ±35 degrees and ±15 mm respectively.

III. Experiments

A. *Setup time and fixing force evaluation*

The proposed fixing device copies the shape of the target in real time and fixes on the surface of target strongly. We evaluated the time that is required to setup the fixing device on target. The setup time depends on the inner volume of the jamming suction pad. We measured the time required for the gauge pressure to change from 0 Pa to maximum vacuum. After that, we evaluated the fixing force of suction pad from the maximum vacuum pressure and the area of suction pad. To evaluate the air-leak amount of suction pad on curved object, we measured the gauge pressure in suction pad when the proposed device is set on a flat plate and curved human-shaped phantom. The trial time of both experiments was 50.

B. *Rigidity under external load*

The rigidity of robotically surgical assistant system in surgery is an important factor for clinical use. The maximum load in the direction of insertion that is expected during surgery is around 25 N [9], and the thrill applies load in different directions. The stiffness of the fixing part and the mechanical part relates to the rigidity of the system, and we tested this parameter by adding 25 N insertion load to the needle when the needle is set in the needle guide. The stiffness of the proposed system were evaluated by measuring how well the geometrical relationship between target and proposed systems is maintained. The displacement of the external load directly relates to the accuracy of needle insertion. We attached three-dimensional position markers to measure the displacement of the fixing device and the needle guide while on the phantom coordinate system during needle inserting operation. The experimental setting condition is shown in Fig.7. The diameter of Kirschner wire was 3.0 mm and 25 N was added without screwing. The insertion direction of the needle was evenly divided up 25 angles in working range, 2 times each direction. The target was a human-shaped phantom that was fabricated from acrylic resin (Fullcure720, Stratasys Ltd.) by 3D Printer (Objet EDEN260V, Stratasys Ltd.) with considering the shape information of patients. The dimension data of this phantom was the dimension and shape model produced by Kawauchi; the homology average dimension and shape model. The translation drive axis were fixed, and the rotation drive controlled the orientation of needle insertion.

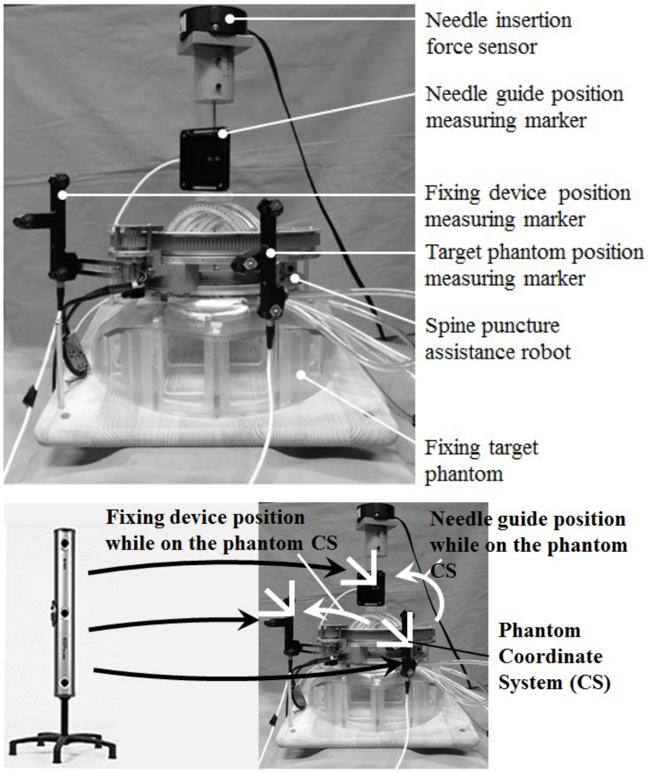

Figure 7. Experimental setting and the measuring position of the rigidity evaluation during needle insertion operation.

C. *Needle positioning accuracy*

Accurate positioning of needle guide is necessary for robotically-assisted spine punctures surgery. The positioning accuracy of axes is related to the positioning accuracy of the needle guide. We evaluated the positioning accuracy of each axis. To measure the positioning accuracy, we attached an infrared measurement marker of the three-dimensional position measurement device (OPTOTRAK, Northern Digital Inc., Canada) to the needle guide and measured the position of the marker while driving each axis. Each single axis were driven to the target position and orientation within the driving range. The target points were set equally spaced and the driven axis stopped these points during shuttling from end to end of the range. The cycle number of the repetition was 5. The accuracy of controlling the needle guide's position and orientation was evaluated by calculating the error between target values and measured values.

IV. RESULTS

The amount of time required for the setup the device onto the target is shown in TABLE I. The average time was 1.6±0.1 second. The fixing force by the suction pad was 172±6 N on the flat plate and 166±8 N on the human-shaped phantom. This result is shown in Fig. 8. The result of rigidity evaluation is shown in TABLE II and TABLE III. The displacement of the fixing device was 0.05±0.03 mm and 0.02±0.02° in average, and 0.06 mm and 0.02° in RMS. The maximum displacement of fixing device was 0.20 mm and 0.10°. The total displacement at the needle guide was 1.43±0.84 mm and 1.11±0.55° in average, and 1.66 mm and 1.24° in RMS. The maximum displacement of the needle guide was 3.14 mm and 2.13°. The accuracy experiment results of needle guide positioning are shown in TABLE IV. The total positioning error of the needle guide control device was 0.09 mm and 0.97° in RMS error. The total maximum positioning error was 0.18 mm and 1.57°.

TABLE I
SETUP TIME FOR PROPOSED DEVIECE TO TARGET

Time to vacuum air [second]	1.6±0.1

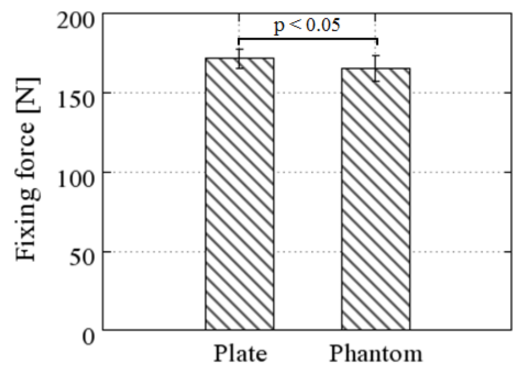

Figure 8. Fixing force when the fixing device is set on the flat plane and the human-shaped phantom.

TABLE II
DISPLACEMENT OF FIXING DEVICE DURING NEEDLE INSERTION

	Positional displacement [mm]	Angular displacement [degrees]
Mean±S.D.	0.05±0.03	0.02±0.02
RMS displacement	0.06	0.02
Maximum displacement	0.20	0.10

TABLE III
DISPLACEMENT OF NEEDLE GUIDE DURING NEEDLE INSERTION

	Positional displacement [mm]	Angular displacement [degrees]
Mean±S.D.	1.43±0.84	1.11±0.55
RMS displacement	1.66	1.24
Maximum displacement	3.14	2.13

TABLE IV
POSITIONING ERROR OF EACH AXIS

	Position		Orientation	
Axis	t [mm]	θ [degrees]	α [degrees]	β [degrees]
RMS Error	0.09	0.07	0.84	0.48
Maximum Error	0.17	0.19	1.34	0.81

V. DISCUSSION

The amount of time required for spine puncture surgery is either equaling or surpassing an hour. The setup time is uninfluential in this condition.

The fixing force of the proposed device on human phantom is significantly smaller than when on flat object, and it shows that the shape of an object relates to the fixing performance of the proposed device. If the outer edge of suction pad follows the shape of the human phantom and is fixed, the air sealing seat works just as well as on the flat plate. The reason that the performance is different between different shapes is the outer edge does not contour to the surface of human target because the particle does not crowd into this region at initial setup. The initial particle filling should be tailored to the shape of the target, and it relates to the flow property of the particles.

The displacement of the fixing device during needle inserting operation is small in regard to the 1 mm and 1° target accuracy. The fixing device connects directly to the base of the needle guide control device. When the fixing device is fixed on human-shaped phantom, it maintains the geometrical relationship of the target and the base of body-mounted robot well when the target is rigid body. The rigidness of the proposed system is enough as a fixing device for the human-shaped phantom. The difference between the phantom and patient's body is another concern in this experiment. In clinical condition, the other properties of patient body and deformation should be considered to maintain the coordinate system relationship between robot and affected area. The effect of the proposed fixing device on the human body surface is going to be evaluated by the additional experiment using human body surface, and optimization of size and arrangement of fixing device has to be done.

Positional and angular displacement of needle guide was somewhat larger. Reasons of the error are deformation and the backlash of the needle guide and the orientation control part. Currently, the needle guide and the orientation control part are made of acrylic resin and this is a straightforward method to ensure greater X-ray transparency. However, as the acrylate resin is inferior in rigidity, some deformation occurred during the needle insertion. As the acrylate resin is lack of lubricity, some gap is needed to drive the needle guide along the curved guide smoothly. This gap caused backlash during the needle insertion. Replacing some parts of the needle guide and the orientation control part to hard-rigid materials; metal and optimization of the contacting method of the needle guide and orientation control part would overcome deformation and backlash. Also, image processing technique to reduce artifacts from the metal parts should be considered.

The aim accuracy of the needle guide control is positioning error less than 0.1 mm and 0.1°. The accuracy of position control was enough compared with the aim accuracy. Though, the accuracy of orientation control was not acceptable. The reason for the error in orientation control is backlash caused by the 45 degree bevel gear and the gap between the needle guide and curved guide.

VI. CONCLUSION

In this study, we proposed a surgical instrument for fixing a medical device using the jamming transition phenomenon and the needle guide control device for spinal puncture surgery. We developed a prototype and evaluated its performance. As the result, the setting time of fixing device was 1.6 ± 0.1 seconds and doesn't bother surgeons. The fixing force of the proposed device on human shape phantom was 166±8 N and is enough to fix the spine surgery assistance device weighting 1963 g on the human body surface. When this fixing device is set on human shape phantom and 25 N needle inserting force is added, the deviation of the coordinate relationship between the fixing device and phantom was 0.06 mm and 0.02° in RMS. The proposed fixing method can maintain the relationship between the coordinate system of the device and the human-shaped surface with an acceptable level when the target is rigid body. In clinical cases, soft tissue exists between the patient's affected are and the robot and the deformation of soft tissue can become the reason of accuracy decreasing. So, the rigidity of fixation on the human body should be tested to optimize the fixing method in the next step. Displacement of needle guide was 1.66 mm and 1.24° in RMS. Further works will be done in order to improve accuracy and rigidity of the needle guide control device. The needle guide control device worked within 0.1 mm and 1° of RMS error. For clinical application, the accuracy should be improved by the stiffness enhancement of the arch axis parts.

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