35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

A surgical robot with a heart-surface-motion synchronization mechanism for myoblast cell sheet transplantation

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Abstract—**Myoblast cell sheets are employed in the clinical treatment of heart disorders. We propose a surgical robot system with two endoscopic cameras, characterized by a double remote center of motion (RCM) mechanism, to realize heart-surface-motion synchronization movement for myoblast cell sheet transplantation on a beating heart surface. A robot system with the double RCM mechanism was developed for which the linear and rotation motions are totally isolated, and an experiment was conducted to evaluate the tracking accuracy of the robot system when tracking a randomly moving target. The tracking data were updated with a Polaris system at 30 Hz. The experiment results showed linear and rotation tracking errors of 4.93 ± 5.92 mm and 2.54 ± 5.44°, respectively.**

I. INTRODUCTION AND PURPOSE

The progress in medical technologies, especially biomedicine, has placed organ and function recovery through tissue engineering and regenerative medicine in the limelight. Presently, myoblast cell sheets are employed in the clinical treatment of heart disorders (1). Its advantages of little infection risk and no rejection reaction make it a quite promising approach, but problems still remain. For example, the fragile cell sheets can barely be handled without damage to their form or function during the transplantation process, which involves pasting the cell sheets onto a beating heart surface that is moving periodically with six degrees of freedom (DOF) (2). To overcome this obstacle, a surgical robot with a heart-surface-motion synchronization mechanism for myoblast cell sheet transplantation is needed. Several heart-surface-motion-tracking systems have been proposed (3)–(5); however, most are lacking in cost-effectiveness or overly excessive for surgery involving cell sheet transplantation. For example, Toyoda et al. proposed a master–slave surgical robot system with a heartbeat synchronization mechanism for off-pump CABG suturing operations. The tracking experiment results showed that the measured maximum deviation of each axis using a parallel mechanism was less than the expected value of 1–2 mm. However, as our objective was to reduce the mechanical damage to the cell sheet during the transplantation process, such high accuracy is not required. Many methods can capture the beating heart surface motion data. To ensure the measurement accuracy, methods such as attaching several markers or sensors to the heart surface are used. As our aim was to complete robot-assisted cell sheet transplantation, we wanted to perform the transplantation process without putting any markers on the heart surface as they may act as obstacles to tissue transplantation.

We propose a surgical robot with a heart-surface-motion synchronization mechanism for myoblast cell sheet transplantation. The concept of the system is shown in Figure 1. The surgical robot comprises three parts: two endoscopic cameras, a robot system, and a PC. To realize the goal of transplanting myoblast cell sheets while not placing any burden on the heart, the system includes two endoscopic cameras to obtain the heart-surface motion without making contact with the heart. To eliminate unnecessary functions and improve the reliability of the entire system with high cost-effectiveness, our proposed robot system is specially designed for myoblast cell sheet transplantation. In this paper, we introduce our concept and a prototype of the cell sheet transplantation robot with 6 DOF motion. We evaluated the accuracy of the motion compensation ability of the prototype using simulated motion data of a heart surface.

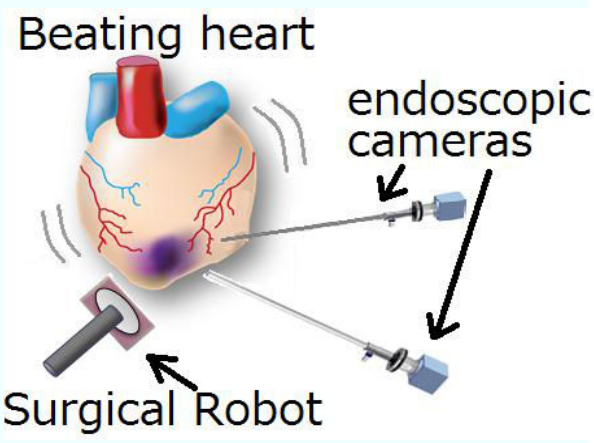

Fig. 1 The system concept

II. METHOD

A. Robot system

1) Requirement: Under normal conditions (no stabilization, 60 beats/min), the experiment object—i.e., heart—has a peak velocity on the surface of more than 0.1 m/s. The highest acceleration can be up to 10 m/s^2. In order to track this movement, an update rate of at least 20 Hz is thought to be appropriate (6) (7). Based on data from an *in vivo* experiment, the beating heart of a pig moves up to 140 mm linearly and 13° rotationally along each axis. A machine with motion compensation ability is needed to track the object accurately.

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*Resrach supported by the Fund for the Improvement of Research Environment for Young Researchers of MEXT, KAKENHI Grant-in-Aid for Young Scientists (A) of MEXT (23680056), and Konica Minolta Science and Technology Foundation.

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978-1-4577-0216-7/13/$26.00 ©2013 IEEE

SCARA robots are widely used as tracking machines in factories and industries. In the laboratory, the parallel robot is receiving attention for its high stiffness and high acceleration. However, using the SCARA robot requires a huge amount of space to ensure that the robot does not hit obstacles. For both robots, big gestures need to be made to produce a rotational movement.

We needed a machine that can track an object at more than 0.1 m/s and accelerate at more than 10 m/s^2. The moving range should cover more than 150 mm on each axis. All of the tracking calculations for each circle should be finished within 50 ms. For myoblast cell sheet transplantation, the machine should be able to work in an operation room; it needs to make both linear and rotational motions without requiring large movements in a limited space. This is to realize the goals of working in limited spaces like an operation room and via rotational movements that do not change the robot's gestures.

2) Cell Sheet Transplantation Robot with Double RCM (remote center of motion) mechanism: To realize the goals of working in a limited space and rotational movements that do not change the robot's gesture, our proposed concept is as follows. Since we cannot make a 6 DOF robot that can be used in a limited space, we can separate the robot into two 3 DOF robots: on for linear movement and the other for rotational movement. Thus, the linear and rotational movements need to be separated.

We used three sets of servomotors and actuators to generate the linear movement. To separate the linear and rotational movement, the pivot point should be totally static during linear movement. Otherwise, a rotational movement will still require linear compensation. Thus, we propose a double remote center of motion (RCM) mechanism to realize a 2 DOF rotational motion. There are different ways to realize a mechanically constrained RCM (8): parallelogram linkages (9) or other linkage configurations. However, in most solutions, the actuators are located directly on the joints, increasing the links' inertia and thus affecting the robot's performance (10). Mechanically constrained RCM, passive RCM, and virtually constrained RCM (11) each have their individual advantages. Constrained RCM is usually preferred as it is considered safer than the other approaches, and virtually constrained RCM is advantageous in a limited space. In this study, we chose virtually constrained RCM for two reasons: we are making small and quick motions in a limited space, and we require space for other works.

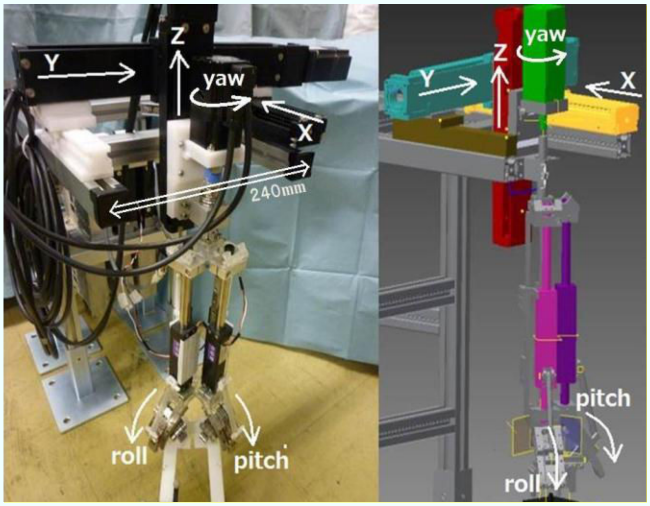

Fig. 2 Distribution of the 6 DOF of the robot system.

Figure 2 shows the structure and distribution of the 6 DOF of the robot system. For the linear part, we used three sets of a servomotor and actuator. The actuators were connected vertically to each other. The X axis was fixed to the aluminum frame. Beyond the X axis, the Y axis was a crosswise beam of the robot. The Z axis hung off it. The effective strokes of the actuator along the X, Y, and Z axes were 167, 217, and 167 mm, respectively. The double RCM mechanism was fixed to the actuator of the Z axis; the end-effector, which was designed for myoblast cell sheet transplantation, was at the front of the rotation part. As shown in Figures 2 and 3, two shaft motors were used to drive the 2 DOF rotational movements though a magnet pillar rail. Two links connected the two shaft motors and bigger R guide rail. Two big guide rails were set vertical to each other; their virtual pivots coincided, and the rotation axis stayed on the same vertical plane—i.e., the virtual transplantation plane. Two small R guide rails were also vertically set on the bigger guide rails. Their pivots were also on the axis of the virtual transplantation plane; the two small guide rails were connected by one element with a virtual plane designed for setting the cell sheet and transplantation. Thus, the two unconnected and differently sized guide rails shared the same rotation axis and made the same rotational movements without moving the central pivot on the virtual plane. The other pair of guide rails' movement was the same. Both the big and small guide rails had a rotational range of 20°. In addition to the 2 DOF of rotation, one more rotational movement was generated by a connected servomotor at the top of the double RCM mechanism; the rotation axis was also through the pivot point on the virtual plane. All these structures allowed the linear and rotational movements to be separated.

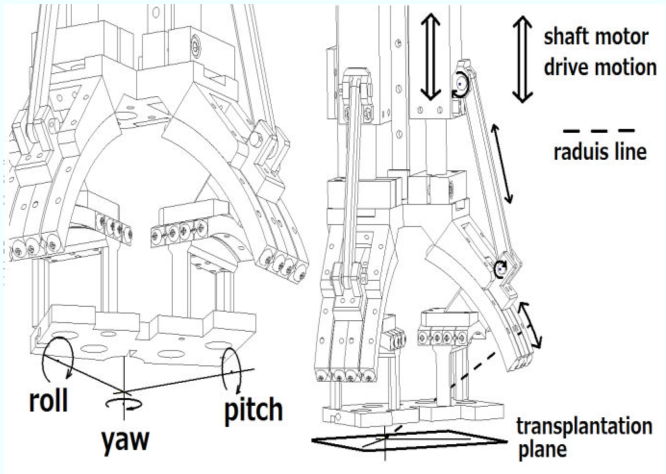

Fig. 3 Double RCM mechanism

B. Experiment

1) Accuracy experiment: In the initial laboratory phase, testing our synchronization mechanism system directly *in vivo* was not thought to be appropriate; therefore, we designed a testing system to evaluate the position synchronization performance and synchronization transplantation operability. We used a 3D optical tracking system (Polaris SPECTRA, Northern Digital Inc., Canada) for this testing system. The X, Y, and Z axes of the robot system were defined as parallel to the actuators of the X, Y, and Z axes, respectively. The PC (CPU: Core i5-650 3.20 GHz RAM: 2.00 GB 32 bit) was in charge of exchanging data and controlling the whole system. Figure 4 shows the experimental system.

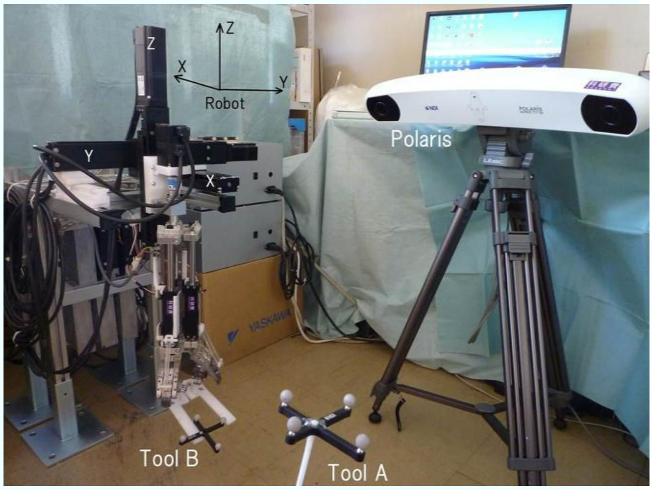

Fig. 4 The testing system

To evaluate the system synchronization performance and robust characters, we used 6 DOF motion data generated by the rigid body marker tool of Polaris SPECTRA. One rigid body marker tool (Tool A) was used to generate the "source" movement, which was moved randomly by the experimenter. The motion data of Tool A was used to generate the control commands for the robotic system, and the robot actuators were synchronized with the motion of Tool A. Another rigid body marker tool (Tool B) was fixed to the front of the end-effector of the robot system to record the robot system's motion. The central point of Tool B was set to register the center of the virtual plane of the end-effector, which was designed to assemble the myoblast cell sheet for transplantation. In this process, both sets of motion data from Tools A and B were updated at 30 Hz. Finally, we compared the data to evaluate the accuracy of the robot movement.

III. RESULTS

A. *Tracking testing*

Table I shows the linear deviations of the robot system tracking motion for 3 DOF, and Table II shows the rotational tracking errors. The average linear and rotational tracking errors over one experimental trial were 4.93 ± 5.92 mm and 2.54 ± 5.44°, respectively.

TABLE I. LINEAR TRACKING ERRORS (MM)

LINEAR AXIS	X	Y	Z	TOTAL
ERROR	2.75 ±3.49	2.76 ±3.21	3.03 ±3.54	4.93 ±5.92

TABLE II. ROTATION TRACKING ERRORS (°)

ROTATION AXIS	X	Y	Z	TOTAL
ERROR	1.38 ±2.36	1.26 ±2.38	1.72 ±4.29	2.54 ±5.44

Figure 4 shows the linear tracking displacement on the X axis, and Figure 5 shows the rotational tracking angle on the X axis for one experiment.

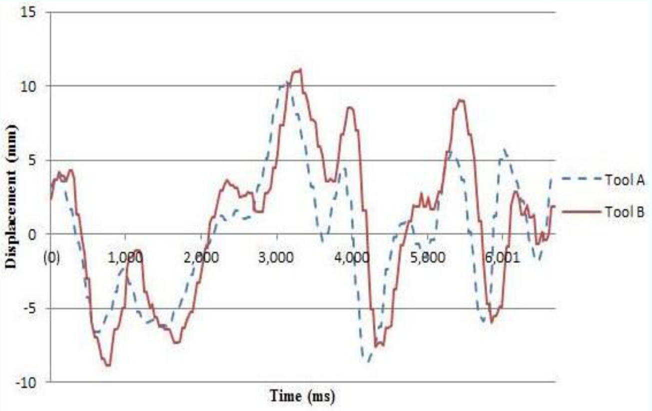

Fig. 5 Linear tracking on X axis (mm)

IV. DISCUSSION

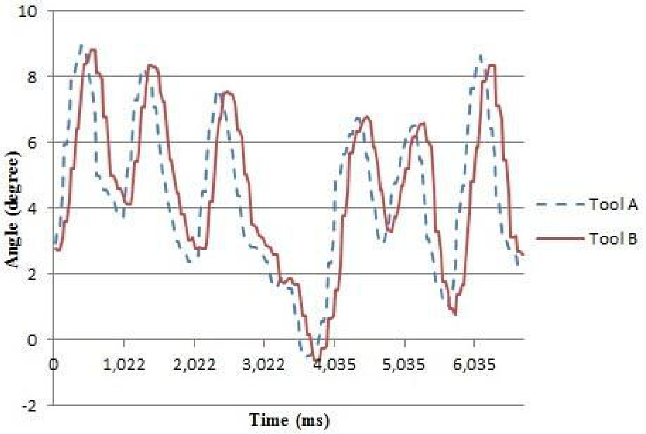

Fig. 6 Rotation tracking on X axis (°)

Based on the experimental results, our robot system can transplant myoblast cell sheets at a sufficient update rate and tracking speed excluding the rotational movement on the Z axis. Our objective was to reduce the mechanical damage to the cell sheet during the transplantation process. This process does not require the accuracy to be as high as that for a robotic suturing system performing coronary bypass surgery. Therefore, we analyzed the mechanical stress on the cell sheet during this transplantation process to optimize the control methods. With regard to the range, although the linear tracking range was satisfactory, the rotational tracking movement on the X-axis had a range of 8°, which was less than the required 13°. This is because we restricted the motion range of the shaft motors to prevent accidents from excessive range; this problem can be solved by enhancing the control program. If we parallel-translate the data from Tool B forward about 120 ms, we would obtain a linear tracking error of 3.09 ± 3.65 mm, which means that the time delay has a big influence on the tracking deviation. To overcome this problem, we are equipping a program to predict the surface motion of a beating heart in the next stage.

We considered the reason for the huge deviation in the rotational movement on the Z axis and connected the rotation part directly to the servomotors. Due to the inertia effect, the system greatly vibrates on the Z axis. To compensate for this deviation, we can equip a connection between the servomotor and actuator, such as a harmonics gear, to reduce the inertia effect on the servomotor.

For the overall robot system, system vibration also has a big effect on the tracking process. Because we simply placed the robot system on the ground instead of fixing it (Fig. 2), the robot vibrated when tracking an object at high speed. We are planning to fix the robot directly to the ground to reduce the influence of vibration.

V. CONCLUSION

We proposed a surgical robot with a heart-surface-motion synchronization mechanism for myoblast cell sheet transplantation. This system was designed to focus only on myoblast cell sheet transplantation; unnecessary functions were discarded to improve the reliability of the overall system. We designed a testing system to evaluate the tracking motion error of the robot system. The testing system updated data using a Polaris system. In the experiment, the tracking error of each axis' linear movement was 4.93 ± 5.92 mm, and the error of the rotational movement was 2.54 ± 5.44°.

Based on the tracking test results, our designed robot system has the potential to compensate for the motion of organs like a beating heart surface, but we still have to improve the tracking accuracy to achieve a performance appropriate for transplantation. At present, the objective cannot be fulfilled due to a design flaw regarding the rotational movement on the Z axis; we will fix this mistake in the next stage by using a connection part between the servomotor and double RCM mechanism. The stiffness of the whole system will also be increased to reduce the vibration problem.

ACKNOWLEDGMENT

We thank Professor Tatsuya Shimizu of Tokyo Women's Medical University for his support and advice on cell sheet engineering techniques and the clinical requirements of cell sheet transplantation for heart disease.

REFERENCES

[1] T. Shimizu, M. Yamato, A. Kikuchi, and T. Okano, "Cell sheet engineering for myoblast tissue reconstruction," *Biomaterials*, vol. 24, no. 13, pp. 2309–2316, 2003.

[2] P. Cattin, H. Dave, J. Grünenfelder, G. Szekely, M. Turina, and G. Zünd, "Trajectory of coronary motion and its significance in robotic motion cancellation," *Eur. J. Cardio-Thorac Surg.*, vol. 25, pp. 786–790, 2004.

[3] Y. Nakamura, K. Kishi, and H. Kawakami, "Heartbeat synchronization for robotic cardiac surgery," in *Proceedings of the 2001 IEEE International Conference on Robotics & Automation*, [], 2001, pp. 2014–2019.

[4] K. Okada, A. Kato, T. Noguchi, K. Toyoda, K. Kawamura, Y. Kobayashi, J. Okamoto, T. Miyashita, and M. Fujie, "Robotic heart-beat simulator to evaluate a surgical robot system with heart- beat canceller," in *Proceedings of the 2008 JSME Conference on Robotics and Mechatronics*, 2008.

[5] K. Toyoda, J. Okamoto, K. Kawamura, Y. Kobayashi, H. Takemura, and M. G. Fujie, "Development of master-s lave surgical robot system with heartbeat synchronization mechanism (evaluation of position synchronization performance and synchronization suture operability)," *Journal of the Japan Society of Mechanical Engineers*, vol. 77, pp. 778, 2011.

[6] C. N. Riviere, J. Gangloff, and M. de Mathelin, "Robotic compensation of biological motion to enhance surgical accuracy," in *Proceedings of the 2006 IEEE*, 2006, vol. 94, no. 9, pp. .

[7] E. Bogatyrenko, P. Pompey, and U. D. Hanebeck, "Efficient physics-based tracking of heart surface motion for beating heart surgery robotic systems," *CARS* vol. 6, pp. 387–399, 2011.

[8] M. Turner, D. Perkins, A. Murray, and P. Larochelle, "Systematic process for constructing spherical four-bar mechanisms," in *ASME International Mechanical Engineering Congress and Exposition*, [city], [state], 2005, pp. [page numbers].

[9] R. Taylor, J. Funda, B. Eldridge, S. Gomory, K. Gruben, D. LaRose, M. Talamini, L. Kavoussi, and J. Anderson, "A telerobotic assistant for laparoscopic surgery," *IEEE Engineering in Medicine and Biology Magazine*, vol. 14, no. 3, pp. 279–288, 1995.

[10] P. Berkelman and J. Ma, "A compact, modular, teleoperated robotic minimally invasive surgery system," in the *1st IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics* (*BioRob*), , 2006.

[11] G. Guthart and K. Salisbury, "The inituitive telesurgical system: Overview and application," in *Proceedings of the 2000 IEEE ICRA*, , 2000, pp. 618–621.