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Robotic Creation of Operating Space for Minimally Invasive Hip Joint Surgery

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Abstract— **Hip joint surgeries are commonplace in our aging society. Robotic hip joint surgery is performed to cut bone precisely and is expected to be performed as minimally invasive treatment. Minimally invasive hip joint surgery needs operating space between muscle tissues and the bone around hip joint. In this paper a prototype of an articulated muscle-retracting robot for minimally invasive RAO (Rotational Acetabular Osteotomy and one of the hip joint surgeries) is described. The muscle-retracting robot's role is to create an operating space between muscles and the surface of the bone for the other robot, whose role is to cut bone. The mechanical structure is very thin to follow a narrow path and tough enough to scrape and retract muscles around a hip joint. The prototype is designed based on the required specification from the previous experiments data. The prototype has 9 DOF, in which 3 DOF arms are capable of controlling the tip position and the force between muscle tissues and the surface of the bone. Evaluation of the prototype was done by using a compliant control as scraping method of muscle tissues from surface of the bone. The capability is revealed as a scraping length on a phantom of 140 mm around human hip joint model and on the living tissues of 27 mm in the crest of the ilium by magnitude of maximum force of 25 N. The scraped living tissues were a narrow part around the hip joint. We shall continue to research it and establish a stable control method to scrape tissues.**

I. INTRODUCTION

A. *Robotic Hip Joint Surgery*

Robotic surgery requirements are increasing ever further, since dexterity for operations successfully brings prospects and technique to surgeons. Robotic surgery can offer patients treatment with only a slight load exerted. 10 million people have hip joint diseases worldwide and there is a significant need for hip joint surgery in the ageing society. Hip joint surgeries are divided into two operating methods [1]. One involves the artificial joint replacement of one or all parts. Another one is osteotomy, involving cutting the bone to correct the position of the real hip joint using cartilage. The operating method depends on the condition of the patient's hip joint. Many surgical robots applied to artificial joint replacement that have provided good results for patients have been developed [2]-[5]. These robots can cut bone to precise shapes, planned by using Computerized Tomography scans (CT) and a pre-planning system. During the surgical procedure, the robot needs operating space to cut the bone and prepares the cavity for the artificial implant. The surgeon then largely incises the skin, scrapes the muscle tissues from the surface of the bone, and exposes the bone of the joint.

A growing trend in recent years has seen the manually operating method progress from a large to a small incision, to reduce the load on the patient. Surgeon performs an operation using an endoscope and certain surgical instruments [6], [7] (Fig. 1). Treatment with a small incision is known as minimally invasive surgery and performed to a part of artificial joint replacement. However, few surgeons can perform hip joint surgery through a small incision because doing so hampers efforts to manipulate the surgical instrument with dexterity [7]. Considerable practical experience is required to acquire the surgical skills to operate safely. In the case of osteotomy, minimally invasive treatment is impossible using conventional rod-type instruments because of the complex cutting shape (Fig. 2). Some bone cutting robots have been developed for minimally invasive treatment [8]. However, these only apply to certain operating methods of artificial joint replacements because there is no operating space. Therefore the operating space is the most important aspect in performing minimally invasive hip joint surgeries and articulated structural instruments must establish an operating area.

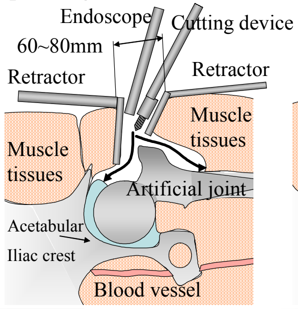

Fig. 1. Conventional minimally invasive surgery

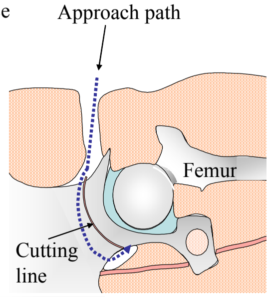

Fig. 2. The required approach in minimally invasive surgeries

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B. Operating Space in Minimally Invasive Surgery

The operating space is full of muscle tissues, including the nerves and blood vessels between the skin and surfaces of the bone around the hip joint. Muscle tissues adhere to the bone through the layer of periosteum. Muscle tissues must be scraped and retracted with the periosteum along the bone for the operating space, whether the procedure for a large or small incision case is undertaken. Blood vessels and nerves are important to control the muscle movement of lower limbs. Surgeons need to scrape muscle tissues carefully along the bones so as not to damage muscle tissues, nerves, and blood vessels. In the case of a large incision surgeons can manipulate surgical instruments while confirming their position under direct view. With a small incision, the surgeon needs to do so while viewing an endoscope image and predicting their position hidden in muscle tissues. Advanced technique, knowledge, and considerable experience are all vital in order not to damage either nerves or blood vessels. Therefore, the operation is very difficult, making considerable demands of the surgeon. In recent years, certain robots for laparoscopic surgeries have been developed [9], [10]. These robots have articulated structures, like a human wrist with end forceps. However these human-wrist type robots cannot correspond to curves around the hip joint while scraping and retracting muscle from the surface of the bone through a small incision.

In this research the target is to develop an articulated robot that can create safety enough operating space between muscle tissues and surface of the bone to cut the bone safely. The articulated robot moves around hip joint through a small incision while scraping and retracting muscle tissues. The articulated robots are integrated with the other articulated robot with a bone-cutting device. The former articulated robots protect blood vessels, nerves, and muscle tissues while the latter robot cuts the bone. Minimally invasive surgery with high safety can be applicable not only to a few methods of artificial joint replacements but also many hip joint surgeries, including osteotomy, based on the proposed robotic system. As the first application of this research, RAO (Rotational Acetabular Osteotomy) is determined from many operating methods. RAO is a common treatment used in hip joint surgeries and provides good biocompatibility to the hip joint by using a real hip joint, rather than artificial joint replacement methods [11]. RAO is performed for those with early stage dysplastic hips or congenital dislocation of the hips. In the conventional RAO procedure, the surgeon uses a curving blade in an attempt to cut a bone spherically along the rim of the acetabular. The cut part of the acetabular with femur is separated temporarily from the pelvis. The position and the posture of the cut part are determined for medically normal structure and fixed by some screws. The conventional operation requires a wide operating space to ensure the wide cutting range of the bone around the hip joint. Some bone cutting device has been developed for RAO [12].

The authors propose a new robotic system for minimally invasive RAO, as shown in Fig. 3. The proposed robotic system is composed of two articulated robots, as previously mentioned. One scrapes and retracts muscle tissues along the surface of the bone through a small incision, to create operating space around the hip joint, within which the other then cuts the bone. In this research the former is focused on and defined as a muscle-retracting robot. In this paper, first of all, an overview of the muscle-retracting robot system is described. The motion of the articulated robot is based on a trajectory which the surgeon determines using CT data and a pre-planning system. A flexible endoscope is attached to the tip of the robot to ensure the safety of the muscle tissues. The surgeon can adjust the trajectory using the joystick of a console while viewing the intra-operative monitor of the endoscope. Next, the prototype of the muscle-retracting robot is shown with a mechanical design based on the reported data, indicating the required force to scrape and retract muscle tissues and the motion range around the hip joint. The prototype has 9 DOF, in which the 3 DOF part is driven by belts and the 6 DOF is driven directly by motors and reduction gears. The prototype achieved the required scraping motion in the evaluation by a living porcine hip joint and the human phantom successfully. Chapter 2 shows the concept of the muscle-retracting robot. In Chapter 3 the prototype and the control method are shown, and Chapter 4 shows the evaluation experiment. Finally, Chapter 5 shows the conclusion and future work.

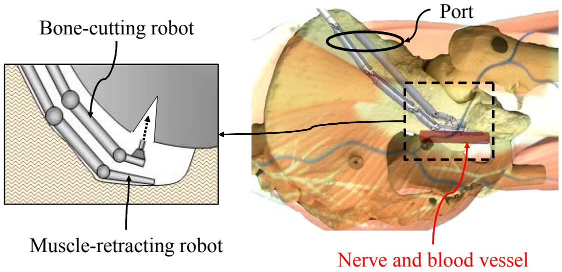

Fig. 3. Conceptual design of surgical robots between muscle tissues and the surface of the bone

II. CONCEPTUAL DESIGN OF THE SURGICAL SYSTEM

The muscle-retracting robot is composed of two articulated arms and a controller (Fig. 4). The controller includes the navigating and manipulating systems for the robot motion. Today, surgical navigation systems are in common use with a diagnostic system and 3D positional sensor used in the orthopedic surgery procedure [13],[14]. CT data is read by a pre-planning system and a hip joint model is created within the system. A surgeon draws the optimum trajectory followed by the muscle-retracting robot in the simulation model. The trajectory data consists of certain points, which have positional information in the bone coordination. The analysis and calculation method of the trajectory data will be described in detail, not here but in the other paper. Markers of the 3D positional sensor are implanted into the robot arm and the patient's bone for registration. An additional implant operation is acceptable for a surgeon because the implant area is part of the area exposed by the small incision. The registration is a process used to determine the transformation matrix from the patient's coordinate system of the CT scanner to the base coordinate system of the robot. The trajectory data of the bone coordination is transformed into robotic coordination. The points of the pre-planned trajectory are prepared by time in robotic coordination. The intra-operative motion of the robot basically follows the trajectory and is additionally manipulated by the surgeon. The surgeon adjusts the tip position and posture using the joystick, while viewing the intra-operative monitor through an endoscope on the tip of the robot to ensure the safety of muscle tissues. The surgeon is also able to implement additional manipulation when suspending or continuing the following motion. In the latter case, the robot is moved along the point data added by the joystick inputs. When suspending, the robot returns to the point at which pre-planned motion was suspended and starts to move along the trajectory again.

The following six points are required to design the robot structure and control:

1) a long and slender shape to enter into the small incision
2) a 3 DOF structure for the motion around the hip joint
3) belts and actuators strong enough to scrape and retract muscle tissues
4) a control method of the position and force of the tip for scraping muscle tissues along the surface of the bone
5) a man-machine interface for doctor's manipulation
6) another compact robot for the support of the 3 DOF robot positioned from outside of the human body (Fig. 4).

The proposed robot arm was divided into two parts for these purposes. One part is "Micro-Arm", which has 3 DOF and enters into the small incision (Fig. 3). The other part sees the "Macro-Arm" have 6 DOF and positions Micro-Arm outside the small incision (Fig. 4). As the simultaneous movement of two arms, the Macro-Arm is moved to position Micro-Arm. The small position and the force of the tip depend on Micro-Arm in the small incision. The required force of the tip for scraping muscle tissues has been already reported [15].

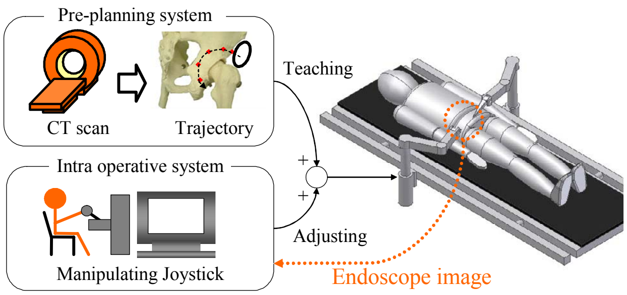

Fig. 4. Robot system Overview

III. THE PROTOTYPES OF THE PROPOSED ROBOT

The overview of the prototype is shown in Fig. 5. The mechanical parameters of the prototype are shown in Fig. 6 where the operating table was seen from the head side.

A. Mechanical Structure of Micro-Arm

The mechanical structure and controller of Micro-Arm are designed to scrape muscle tissues by a tip knife around the hip joint thorough a small incision. A prototype of Micro-Arm is shown in lower left of Fig. 5. In conventional surgery, the surgeon scrapes muscle tissues by using an knife-like instrument. The tip part is fabricated to be like a knife. The prototype includes 3 DOF (1) (2) (3). The link lengths are chosen to reach the deep end of the hip joint through the small incision in the human phantom. The width of 15 mm and the thickness of 6 mm are chosen from a conventional instrument and are determined based on the intensity calculation using the previous experimental result [15]. The torques required to scrape muscle tissues are calculated from the reported force and are 0.3Nm in articulation (1), 0.5 Nm in (2), and 0.8 Nm in (3) respectively. Brushless DC motors (made by the Maxon company and of type 200142) are chosen as actuators for their compact size and high torque. The reduction gears are Harmonic Drive, of which the reduction ratios are 100 times (made by the Harmonic drive systems company and of type CSF-8-100-2XHF). The torque of each articulation is transmitted via the fiber belts in the links from the pulley driven by the motor with the reduction gear. A tension sensor was placed on a belt to measure the torque of each articulation. An articulation is connected to a pulley by 2 belts as shown in Fig. 7. Each belt is threaded in the rotating center like an early surgical robot with wire driven mechanism [16]. The angle of the motor is calculated from an encoder (made by MUTOH Engineering Company and of type UN-2000) and the bending angle is calculated from the belts length rolled up to the pulley. Moreover the extended length of the belt is calculated, based on the previously measured stiffness, to detect the actual angle accurately.

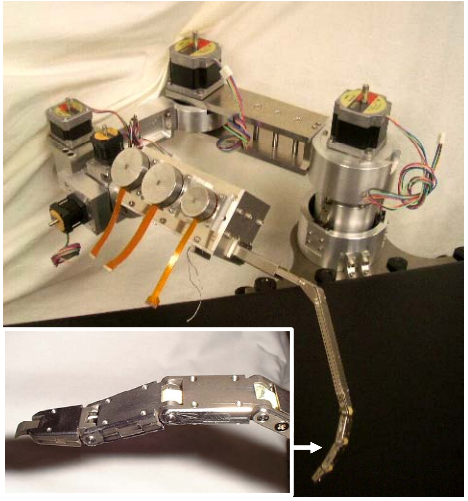

Fig. 5. A prototype of the muscle-retracting robot

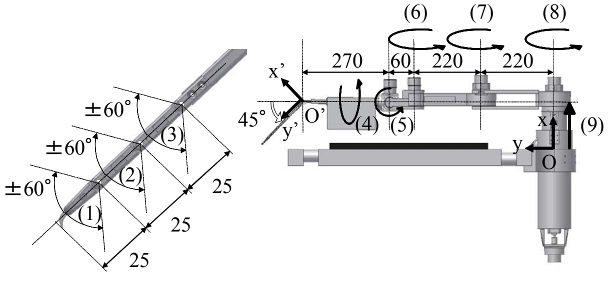

Fig. 6. Mechanical parameters of muscle-retracting robot

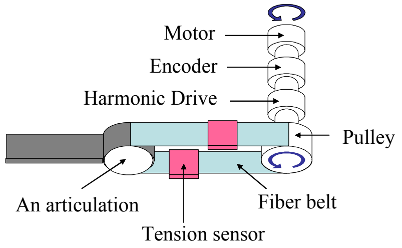

Fig. 7. Drive mechanism of Micro-Arm's articulation

B. *Mechanical Structure of Macro-Arm*

The mechanical structure and controller of Macro-Arm are designed to position the Micro-Arm from the robot base fixed to an operating table side to a small incision. The Macro-Arm is a 6-axis SCARA robot, with a prismatic axis (9), two revolute axes (8) (7), 3 wrist axes and (roll (6), pitch(7), yaw(8)); referred to in the early research "Brain Retract Manipulator" [17]. The Macro-Arm base, fixed onto the rail of the operating table, allows effective use of the space in a crowded operating theatre environment. In the case of the patient's right leg, the arm fixed to the left rail approaches the inside of the bone, where there are visceral organs. The other arm, fixed to the right rail, is inserted externally, at the crest of the illium. Both arms have a symmetrical structure, corresponding to both sides of the legs. The position on the rail is fixed without disturbing the surgeon's assistant operation.

The origin O of the arm is defined as the intersection point of the (8) shaft with the plane of the upper surface of the rail. The x-axis is set in the upper direction of the (8) shaft, the z axis in a longitudinal direction, and the y axis in the direction from the exterior product of the x- and z-axes, as shown in Fig. 6. The origin O' of Micro-Arm is set at a 45 degree bending point, as shown in Fig. 6. The bending portion of 45 degrees between articulations (3) and (4) is to avoid the path of the bone cutting robot.

Macro-Arm's link lengths are determined to carry Micro-Arm to the small incision to meet the reported specification [18]. TABLE 1 shows the range of motion of each articulation. In the case of (9) the range was shown as the displacement between a perpendicular foot from the rotation center of (5) to the shaft (8) and O. When muscle tissues are retracted, Micro-Arm retains the angles of the articulations after the Micro-Arm tip reaches the end point of the trajectory and the Macro-Arm moves without changing posture. The high-torque motors (made by the Oriental motor company and CSK566BP) of (7), (8), and (9) are derived from the load of 78N. These large stepper motors are chosen to be controlled and held easily with high torque. Harmonic Drive of (7) and (8) (made by the Harmonic drive systems company and of type CSF-17-100-2UH and CSF-14-100-2UH) and a ball screw (Made by the Misumi company and of type BSX-12-2-300) are chosen as the reduction gears. Small stepper motors (4), (5), (6) (made by the Oriental motor company and CSK544BP) are derived from the required torque to scrape muscle tissues and compact to efficiently use the crowded space near the incision. Reduction gears are Harmonic Drive (of type CSF-8-100-2XHF), while the direction of rotation (4) is converted using a bevel gear. An optical sensor is attached to each articulation to limit the range of motion and set the initial positions.

TABLE1 Range of each articulation motion

	Rotation [degree]					Translation [mm]
Articulation	4	5	6	7	8	9
Minimum	-100	-45	-90	-100	-180	50
Maximum	100	90	90	100	180	280

C. *Controller and Control method*

The controller is shown in Fig 8. PC104 (Made by the ADVANTEC company and of type PCM-3730) is chosen as a main board thanks to its compactness. Some data are transmitted to each PC in the LAN through a hub.

The target trajectory, which is analyzed and calculated by the pre-planning system, is transmitted to the Macro-Arm controller in pre-operation through the hub and the target angle of each articulation is calculated by time. Moreover, the emergency stop switch is connected to the power supply of motor drivers for safety. If perchance an unexpected situation occurs, it is possible to power down and leave the system to operate appropriately and immediately by surgeons.

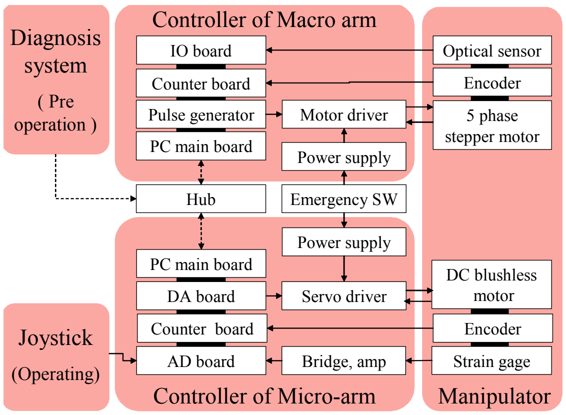

Fig. 8. Control system of muscle-retracting robot

The control method of the proposed robot for scraping muscle tissues is shown in Fig. 9 as a block diagram. The control method consists of a position control loop to follow the pre-planned trajectory around a hip joint through a small incision and a force control loop to scrape muscle tissues from the surface of the bone. Intra-operative motion is based on the position control of the point data (*X target*) derived from the trajectory. The target trajectory data is transformed to the point data group by time. The target angles of 3 DOF are determined from the positional information of the points and geometric parameters of Micro-Arm using a serial calculation method [19]. The serial calculation method leads from the target angle (1) to the target position and posture of the Macro-Arm end O'. The target angles of Macro-Arm are calculated using inverse kinematics. The inverse kinematics of Macro-Arm is defined as *T6* in Fig. 9, while the forward kinematics from O to the Micro-Arm tip is *T9*. The articulation angle error of Micro-Arm occurs from the extension of belt. The real angle (θ_{real}) is detected from the tension sensor value (T), belt stiffness measured previously, encoder value ($\theta_{encoder}$), and articulation radius (r). Belt stiffness is non-linear relation between tension and extension length in a certain range. Belt extension is approximated by the quadratic function $x(T)$ from previous experimental data. The detected angle is not involved in position loop but used to calculate the result of the displacement in this report because we will confirm the control stability by the other extensive experiments.

$$\theta_{real.} = \theta_{encoder} - \frac{x(T)}{r} \tag{1}$$

It is difficult to go over the rough surface of the bone using only the positional control for the following reasons:

1) The low resolution of the positional data obtained from the diagnostic image
2) The positional error derived from the structural stiffness and the servo motor control
3) The registration error between the pre-planned model and the real hip joint.

In addition to positional control, the force-controlled tip blade helps the clean path creation on surface of the bone. The reported data shows the maximum force of 8 N in a tangential direction and 5 N in a perpendicular direction to the surface plane; to scrape muscle tissues from the surface of the bone or ligaments [15]. However, the force-controlled tip is prone to become unstable by the impulse force.

Therefore the compliant relation between the force and position control is used for the stable following motion to the target trajectory instead of the precise positioning and force. The scraping force (Fx) is exerted in tangential direction by the position control (Fig. 10). The tip is capable of continuous contact with the bone by perpendicular force (Fy) control. In the Micro-Arm controller (3 DOF loop in Fig. 9), the target torque is calculated from the target force of the tip, using a transposed Jacobian matrix (J^T) of 3 DOF. The target angle of the inner loop is the sum value of the outer target angle and the multiplied value of the torque error by the compliance (K) as shown in Fig. 9. The articulation torque (τ) is multiplied value of the articulation radius (r) by tension sensor value (T).

In the Macro-Arm controller (6DOF loop) difference pulses between target values and encoder values are sent to each motor. The Macro-Arm positions the Micro-Arm at a low velocity to prevent the impulse force. The tip knife posture is adjusted by joystick input transformed to the tip coordination.

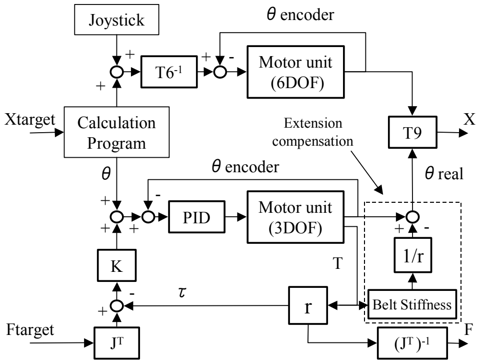

Fig. 9. Block diagram of muscle-retracting robot

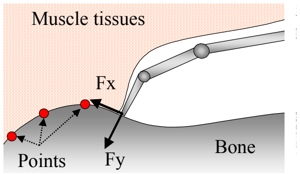

Fig. 10. Constraint motion on the surface of the bone

IV. EVALUATION

The following two points are evaluated:

1) The range of the motion on the human phantom
2) Control method to scrape soft tissues

A. Range of Motion around the Hip Joint

The human phantom of the hip joint and the prototype robot are fixed on the operating table like the actual location. The left of Fig. 11 shows the phantom with material like soft part of muscle tissues. The application is the inside wall of the left hip joint bone. The target trajectory was obtained from the manual teaching method instead of the diagnostic system calculation. As constrained conditions, the tip maintains contact with the surface of the bone and each link is moved near the surface through the small incision to reduce the reaction force from the muscle tissues deformation. The target force is 3 N of perpendicular direction (and tangential force is 0 N), because the adhesion of the soft tissues to the bone there will be weak and easily scraped based on the medical doctor's comment. The value of K is chosen to avoid the singular configuration of Micro-Arm.

The result of the evaluation is shown in the right of Fig. 11 and in Fig. 12, the latter of which includes the target and actually drawn trajectories. The soft materials are scraped from the small incision to the deep part in the hip joint. The length is 140 mm and the scraping motion along the target trajectory is achieved approximately. The actually drawn trajectory is calculated from the encoders of all articulations and extensions of the belt obtained from the tension sensors. The maximum error between the target and actual trajectories was 15 mm near the part of the edge shape part on the surface of the bone. There are variations in the scraped condition caused by the location of the surface. The different rate of the irregular surface results in the variation. The control mode should be changed to lower velocity motion or master-slave dexterity manipulation by surgeon there while following motion is continued or suspended.

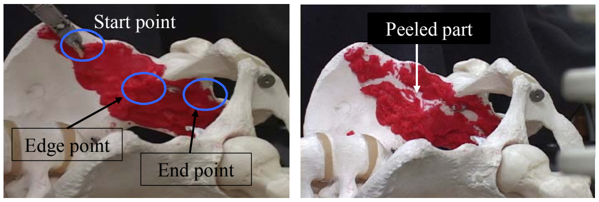

Fig. 11. Hip joint of a human phantom with soft material

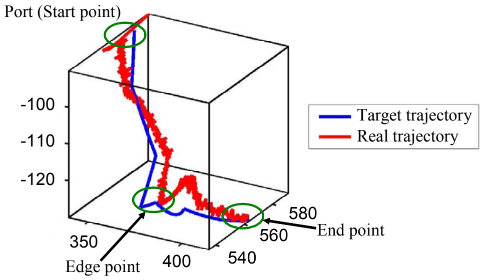

Fig. 12. The tip trajectory in the bone coordination

B. *Scraping Capability toward Living Tissues*

After being successfully tested on the human phantom bones, the proposed robot system was tested on the scraping motion by living tissues of a porcine hip joint (Fig. 13). The surface softly attached to muscle tissues is chosen as the objective surface on the iliac crest because this evaluation covers an early stage of the scraping motion toward varied surfaces and tissues. Because the evaluation focuses on the scraping capability toward living tissues, the test is performed by joystick input without a pre-planned trajectory. The angle of 3 DOF is controlled through 3 axes using a joystick and the target of the tip force is determined based on reported data. The Macro-Arm's direction of movement is manipulated through 6 axes using 12 control buttons (x, y, z, roll, pitch, and yaw in O' coordination). In other words, manual position inputs are used instead of the calculation algorithms of trajectory. Before the evaluation commences, a surgeon opens up a small incision near the objective site. The robot is set on the rail and the tip is manually positioned near the incision. The tip posture is adjusted to facilitate entry, the Macro-Arm is moved to longitudinal and horizontal direction to surface of the bone, at a velocity of 1.5 mm/s, while a button is pushed. The velocity is determined to ensure the safety of muscle tissues including nerves and blood vessels from the opinion of the surgeon. The tip force of Micro-Arm is chosen at 3 N in perpendicular direction (and tangential force is 0 N). Finally, 0.1 degree/Nmm is chosen as the compliance coefficient of each articulation to move stably avoid singular configuration and consider the scraping force. The each articulation is capable of moving elastically like a spring in contacting to the soft tissues and bone. The starting point of the tip was the boundary of the surface of the bone and muscle tissues. The tip was positioned manually as an embryonic evaluation instead of a pre-planed trajectory. The evaluation was done 3 times in similar area of the identical crest of ilium.

As a result, the variation of the force calculated from the 3 articulation torques was plotted versus the tip displacement from the 9 articulation angles in Fig. 14. The data is one of trials and the others appear to be similar tendency. The force is calculated in the coordination of Fig. 10. From Fig. 14, the force increases globally as the tip advances and goes ups and downs several times locally. The actual scraped length is 27 mm in the direction of entry to the deep section, measured using a slide gauge after the experiment.

The maximum scraping force is Fx of 24 N and Fy of 6 N. The perpendicular force is small in starting time and massive toward target value at 18 s. The reason is the difference between estimated and actual height of the surface because of manual positioning of the tip. The contact soft tissues are tough and the required force to scrape is the tangential massive force. In addition we will attempt to compose the stiff motion to create operating space between the ligaments and surface of the bone. It is difficult to scrape ligament and muscle tissues because of the deep position and toughness. Then, we will compose the stiffness-controlled method correspond to contacted tissues types to approach along the tissues boundary.

The scraped path appeared to be formed by the local fractures of the junction between muscle tissues and surface of the bone. The robot tip pushed compliantly the muscle tissues in Fx direction at the localized plots point while the reaction force of the muscle tissues deformation is detected from the articulation torques. Then, the fracture would occur due to increased shear force. Local fractures phenomenon are seen in the scalpel-cutting procedure of the early study [20].

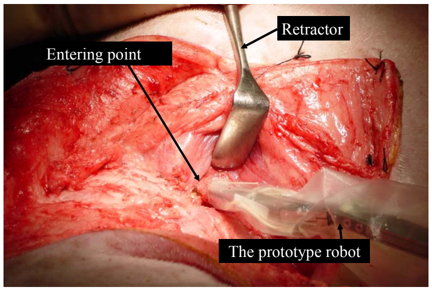

Fig. 13. Experimental over view of porcine hip joint with the prototype robot

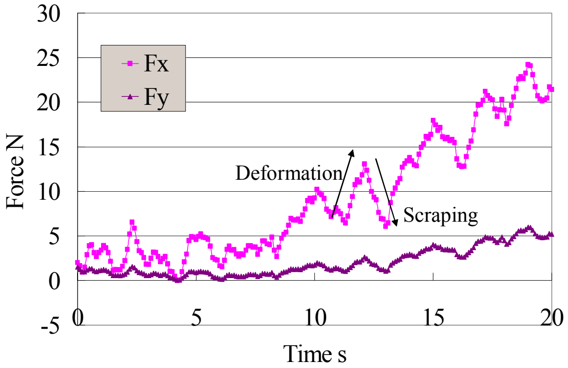

Fig. 14. Relationship between the force value calculated from articulation's torques and the displacement of the tip

V. CONCLUSION

Muscle-retracting robot to create operating space in minimally invasive hip joint surgery has been presented, which was successfully applied to a human hip joint model and living tissues. The robot was divided into two arms for the purpose. Macro-Arm's role is to position the Micro-Arm from outside a small incision. The Micro-Arm's role is to scrape muscle tissues from the bone surface and create the operating space for a bone-cutting robot between muscle tissues and the bone surface. Both arms have a driving ability to scrape and retract muscle tissues while bearing a load. The Macro-Arm is set on the operating table and remains compact without disturbing the assistant surgeon. The structure of the Micro-Arm incorporates a slender body and 3 DOF to enter the small incision and move around the hip joint. The robot is followed to the pre-planned trajectory by a navigation system and manipulated by the joystick handled by a surgeon while monitoring the intra operative endoscope's image. The control algorithm consists of position and force controls of the tip knife respectively. A compliance control must be applied stably to the bone surface while scraping the muscle tissues and a prototype with the control algorithm was evaluated on the human phantom and living porcine hip joint. The robot's capability is proved by the evaluation, in which the robot scraped pseudo muscle tissues of the human phantom to a length of 140 mm and living tissues to one of 27 mm. The magnitude of the maximum pushing force exerted is approximately 25 N on living porcine muscle tissues on the bone. This system ensures a safe surgery through the surgical interface and swift patient recovery. Further, the robot will scrape the ligament that is more tough tissues than muscle tissues scraped in this evaluation. The robot will be integrated with a bone-cutting robot and we compose a system for minimally invasive treatment applied to many hip joint surgeries.

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