Design and Construction of the MU-TKRobot for Total Knee Replacement Application

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***Abstract* - The robotic system is appropriate for orthopedic surgery because the bone structure is rigid so it is easy to be modeled from medical image. Total Knee Replacement surgery is one of the areas that the medical robots are introduced. Distal femur is resurfaced into 5 planes, and, proximal tibia was cut on 1 plane. The development of the robotic bone cutting device is based on kinematic analysis. The requirements were analyzed step by step. The robot was designed and constructed. The robot consists of 4 degrees of freedom. 3 degrees of freedom in translation was constructed to generate a single plane. 1 degree of freedom of circular motion is used to change the position from the reference plane to others plane. The phantom testing is set up on the future plan. This project is working toward the development of MU-TKRobot for TKR application.**

Key words: Total knee replacement, TKR robot, Kinematic Analysis, Design, medical robot

1. Introduction

Currently, a number of robotic applications are employed in various surgical operations which are and resulting in their performance improvement. Orthopedics is one of popular areas that the medical robots are introduced. The orthopedic surgery, from the technical and ergonomic point of view, has a large room to improve the operating performances. Traditionally, the primitive tools, such as, hand held drill and saw are normally used in the orthopedic operations [1]. This may cause not only the fatigue in surgeons from holding equipments but also the insufficiency in performing the tasks. For example, using the oscillating saw in bone cutting results in an error from the blade bending once it touches to the harder part of the bone [2]. The operating performance is truly depending on the surgeon's experience and skill. Moreover, the accuracy is minimized because of the jig-based equipment and vibrated saw. Although the traditional jig-based Total Knee Replacement (TKR) system are able to guide the surgeon for cutting and surfacing the bone into the specific shapes, the conventional jig-based system has some limitations, which could result in an inaccuracy as required for total knee components alignment and the design of the jig. This is because the conventional system is not able to optimize and suit the variation of individual patient's bone [3]. Finally, the surgeon has the human physical limits which are tactile sensitivity, prone to tremor and fatigue [4].

The problems stated above may be solved by applying a designed robotic system to the surgical procedures. With robot-assisted surgery, the task can be planned by using pre-operative image, and the information which is matched to the intra-operative images for the surgical guidance. The surgeon does not require to hold the equipment, and their positioning control in the system could reduce the effect of tremor.

2. Design Requirement for Total Knee Replacement Surgery

Total knee replacement is a procedure to replace distal part of the femur and the proximal part of the tibia in order to repair the improper conditions of the natural knee. This procedure is an extreme case to remove pain from the knee problem. At minimum of two bones are required to be resurfaced to fit with the implant. These bones are distal femur and proximal tibia.

In the distal femur, the bone is normally resurfaced into 5 planes. Each plane is relative to leg alignment. In conventional method, jig-based system, surgeon has to cut distal femur reference to anatomical axis of femur bone cavity. Then, the distal femur is cut by employing specific jig. The first plane is very important because the rest planes are using the first plane as their reference. The errors can be accumulated. For proximal tibia, the surgeon needs to cut bone after complete surfacing plane by plane for one plane, and holes. A slot may be required to fit the prosthesis on the bone. The most important procedure in TKR surgery is bone resections on distal femur and proximal tibia. Their alignment affects the longevity of the knee prosthesis and regains the function of patient.

3. Conceptual Design

MU-TKRobot is designed based on kinematic requirements of TKR surgical procedure.

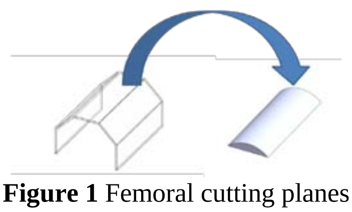

Figure 1 Femoral cutting planes

First, cutting process can be considered. Considering femoral cutting the first plane as show in Figure 1, surgeon is required to cut distal femur into 5 planes. Each piece of bone is considered and cut plane by plane. The next step is tool selection for the robot. Three ways of cutting are usually used to cut the bone hand saw, oscillating saw, and milling (shows in Figure 2). For the simple hand saw and oscillating saw, the blade can be bent while the blade is touching the bone. Oscillating saw is also able to create the problem from vibration. Our purposed tool is milling tool because the tool bit is superior in its rigidity. Moreover, the milling can be used as a multi-tool, such as, drill and mill.

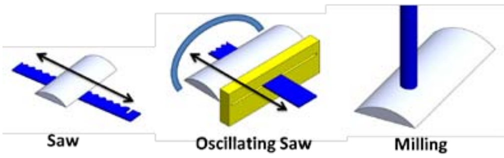

Figure 2 Cutting Process

Next step is considering about motions of tool or degree of freedom for a robot. When, the tool goes along drilling direction as show in Figure 3. Hole can be generated.

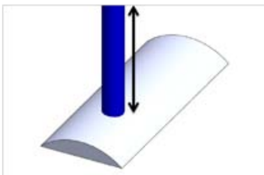

Figure 3 Simulation of drilling

If the tool moves along X direction as show in Figure 4, a slot can be made. But goal of this task is to generate a plane. Then, the robot requires 1 move degree of freedom, to arrange slot to be a plane as show in Figure 5.

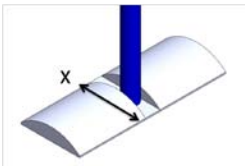

Figure 4 Demonstration of making a slot

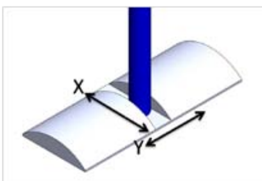

Figure 5 Plane generation

So, plane generation task of the MU-TKRobot requires 3 degrees of freedom in translation as show in Figure 6

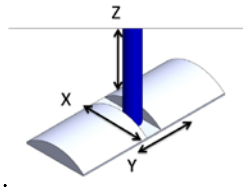

Figure 6 3-DOF for MU-TKRobot

In total knee replacement surgery, surgeon has to cut and resurface distal part of femoral bone into 5 planes and 1 plane on proximal tibia. After, the first plane was created. Next step is to move to another plane relative to the first plane. Especially, the planes on femur, all the plane can be considering as those planes are related to each other by rotating the plane among each other. See Figure 7.

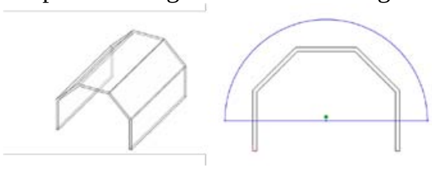

Figure 7 Simulation on 5 planes

After, a center of a circular motion is found. In Figure 8 shows a tool insertion. Tool and planes are in the same center. Tool can go through every plane but a distance between each planes to tip of tool are different.

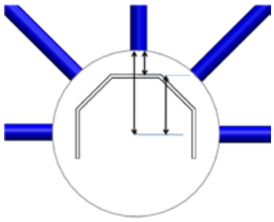

Figure 8 Simulation about tool insertion

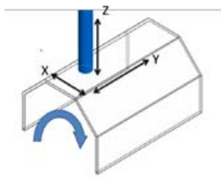

Figure 9 Overall degree of freedom for MU-TKRobot prototype

In this case, a conceptual design of MU-TKRobot in the first prototype consists of 3 degree of freedom in translation and 1 degree of freedom in circular motion or rotation as show in Figure 9.

After the conceptual design is concluded, the next step is to study about a kinematic on bones' surfacing.

4. MU-TKRobot Design and its Kinematic Analysis

For MU-TKRobot is designed to solve the requirement of the conceptual design which have 3 degree of freedoms in translation and 1 degree of freedom in rotation (Figure 3.14).

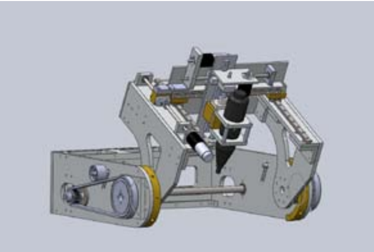

Figure 10 CAD design of MU-TKRobot prototype

CAD design of robot prototype shows that 3 degree of freedom about translation motion will be place on circular motion following the conceptual design.

For circular motion, belt drive mechanism has been used to reduce backlash of circular motion. And idler was used for belt tightening. Motor actuator will drive the mechanism that carry all load of 3 translation motions.

Translation motion will be motor drive a ball screw including linear slide as a guide. Because a ball screw has a high rigidity and can stay at the same position in case of out of electricity or

Tool in the first prototype development, hand drill will be integrated to the end-effecter of MU-TKRobot instead off medical tool.

In robotics has to mention about motion of robot or kinematic of a robot. In this section, the robot kinematic has been analyzed as below.

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$$H = \begin{bmatrix} R(\emptyset) & T \\ \vec{0}^T & 1 \end{bmatrix} \quad (1)$$

H = homogeneous transformation of a robot

For this robot will give a robot rotated by axis.

$$H = \begin{bmatrix} \cos\emptyset & 0 & -\sin\emptyset & P\cos\emptyset \\ 0 & 1 & 0 & 0 \\ \sin\emptyset & 0 & \cos\emptyset & P\sin\emptyset \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$$P = \begin{bmatrix} p_x \\ p_y \\ p_z \\ 1 \end{bmatrix} \quad (3)$$

P is position vector

$$P' = HP \quad (4)$$

P' is a position vector refer to original frame

These will be applied on MATLAB software to study about possibility of robot motion has ability to use in total knee replacement application.

5. Simulation of MU-TKRobot on MATLAB

All planes are combined together as show in Figure 11.

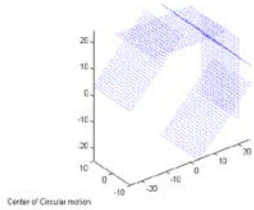

Figure 11 Simulation on all planes

Figure 11 illustrate the robot kinematics which plots for all planes. For making individual plane, the kinematic has to enter only 2 parameters which are the length of the vector or radius and angel of each plane. The simulation shows that kinematic system can be used to generate all planes on femur. And also, tibia plane can be generated by using the same algorithm of the robot kinematic. The algorithm can be used as the geometric constraint for the robot. However, codes for the algorithm need to be improved for the time to generate a plane. Also, a comfortable interface is required for ease of use. In additional, the robot end-effector can be generated on the interface. Surgeon can easily understand when the robot is moved.

6. MU-TKRobot Construction

The prototype is constructed follow a CAD design in solid work. Figure 12 shows Y-axis construction which consists of 1 linear slide, and linear ball screw. The construction is driven by motor actuator with gear head and encoder. For X-axis consists of 2 linear slides and linear ball screw. Motor actuator will use to drive a linear ball screw with same speed as Y-axis as show in Figure 12.

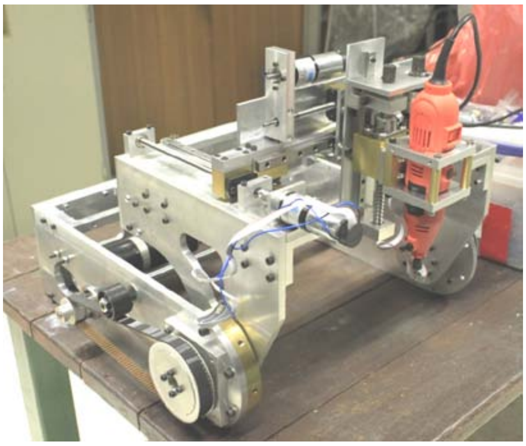

Figure 12 MU-TKRobot prototype

For a circular motion is attached a rotation joint to hold a XYZ structures, get rid of a bending moment affect to the structure. In circular motion, belt mechanism was used to reduce a backlash of circular motion as show in Figure 13.

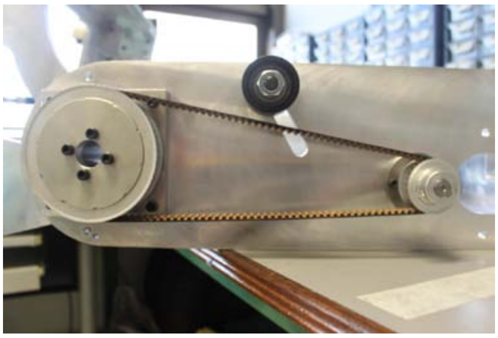

Figure 13 Driven mechanism of circular motion

7. Future Work

Future Work on MU-TKRobot, (1) the first prototype will be test with a phantom. (2) The robot structure is suggested to revise the design to reduce weight and size, however, based on our current idea would give proper results. (3) The design should be mentioned about size, weight, structure, and materials. (4) The ultimate good of this project is to actually use the system in the real practice.

8. Conclusion

The robot is constructed with the circular motion concept. Joint construction has low backlash and high stability. Translation joints can be moved smoothly with low backlash. The robot prototype is tested to access all planes in bone cutting process. The result is very satisfied. Holes and slots can be generated by a robot prototype. Cutting tool is proper to use in the experiment. The robot has some disadvantages, such as, weight and size. The robot weight is 25 kilograms, and the size of the robot is quite large.

In conclusion, (1) traditional total knee replacement surgery requirements was studied in engineering perspective. (2) The conceptual design based on 4 degree of freedom device was discussed. It is including to X-Y translation motion to create a plane. 1 degree of freedom in Z direction is used to adjust a distance between center of circular motion and a plane. (3) The simulation of the concepts was implemented by MAT LAB simulation.

In the future plan, the robot's disadvantages are suggested to be improved, especially, weight and size. The architecture of the robot has to be redesigned more compact. The end-effector of the robot has to be redesigned to easily change the cutting tool. Cutting tool must be changed to medical grade. A high quality controlling system must be integrated in the robot.

9. Acknowledgement

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