The ACROBOT technology: a model for robotic surgery?

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***Abstract*—**the ACROBOT robot for orthopedic surgery is a rare example of a commercial surgical robot which utilizes 3D reconstruction, motion compensation, virtual guidance and haptic feedback. It has been used clinically for minimally invasive Uni-condylar surgery with excellent results. It uses a powered 3 axes robot together with a 2 axes passive orientation device. The system is trolley mounted and designed to fix to the operating room table. The patient motion is tracked using a mechanical arm that updates the plan in real-time. It is suggested that this type of hands-on robot, in which the robot actively constrains the surgeon to an accurate and safe region, is a possible model for other medical robotic systems.

Keywords*—*robotic surgery; orthopedics; ACROBOT; hands-on; Active Constraints.

I. Introduction

The Author started working on an orthopedic surgical robot for replacing hip & knee joints in 1991. This was just after clinical trials on the author's Prostate robot PROBOT [1], when an Orthopedic Surgeon, Prof. Justin Cobb, approached the author saying it must be easier to machine bone as, unlike the prostate, it did not change shape when cut. It was clear from clinical experience with the Probot that surgeons had been trained to have their hands on the patient and so an autonomous system such as the Probot was not appropriate. For this reason a hands-on robot was devised in which the surgeon was directly involved with the robot in a synergistic way [2]. As part of a hands-on robot, the surgeon holds a force control lever at the end of the robot arm next to the cutter. In this way the surgeon can feel forces applied by the robot and at the same time the robot can physically constrain the surgeon to a safe region avoiding cutting critical areas such as ligaments. The robot also enabled minimally invasive surgery, in which a minimal amount of bone stock is precisely removed, enabling small prostheses such as uni-condylar knee replacements, difficult to implement conventionally, to be used instead of much larger total knee prostheses. The system uses a pre-operative 3D CT scan and is a rare example of a commercial surgical robot which utilizes 3D reconstruction, motion compensation, virtual guidance and haptic feedback.

II. THE ACROBOT SYSTEM TECHNOLOGY

A. The Robot and its Control.

The term ACROBOT stands for Active Constraint ROBOT. An Active Constraint describes an approach in which the surgeon is Actively Constrained from damaging critical tissue, such as ligaments, that must be preserved [3],[4]. The constraint prevents the surgeon moving a cutter into a no-go area such as the forbidden zone in Fig. 1, whilst always allowing motion in the central safe zone. As the cutter moves towards the forbidden zone, in the near-boundary area, the force is gradually increased to push the cutter back to the central region or allow it to move tangentially around the periphery.

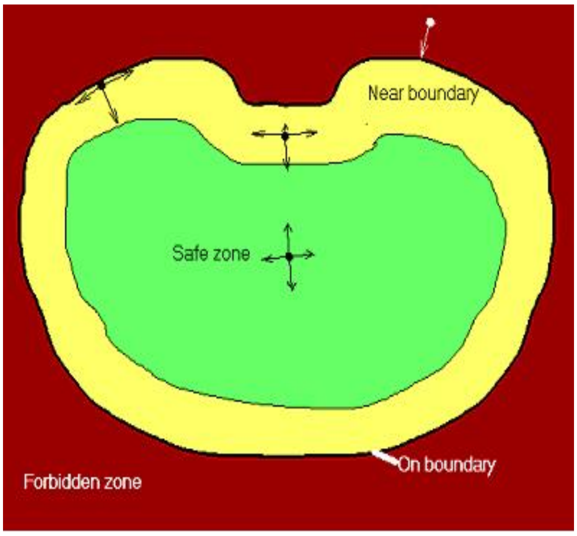

Fig. 1. The Active Constraint concept.

For the robot, 3 motions were powered by DC motors and low friction recirculating ball-screws. For the surgeon to be able to feel the forces applied by the robot in the hands-on mode, the motions need to be even and low impedance, so that the pitch, yaw and in-out motions all have even and low resistance and so there is no tendency for one axis to move preferentially. This was aided by ensuring all 3 axes intersected at a common point. This resulted in sufficient sensitivity that even without the use of a force sensor to amplify forces, the surgeon could feel when cutting a hard piece of bone and slow down or take a lighter cut. This synergy, in which the robot provided constraint and accuracy whist the surgeon was in direct control, proved to be attractive to surgeons.

Originally the robot was mounted on a robotic system which acted as a gross-positioner that was locked off for safety when the small active robot was in the right position and orientation. However, it was found from experience that this large and costly form of gross-positioner was not needed as the cutting forces were light and it was found possible to place the small active robot on a trolley that could be locked to the operating table. Patient motion monitoring was also provided using a mechanical "Microscribe" arm, the tip of which was lightly pinned to the patient's bone [5]. The 6 axes Microscribe arm

was passively actuated and had encoders at all joints and a sufficient update-rate that it could monitor patient motion and change the plan and the cutting constraints in real time to maintain the required cutting accuracy. This avoided the need adopted in early versions for locking down the patient and treating like a traditional CNC machining process. The small active robot utilized 3 powered axes (pitch, yaw and in/out) to provide location whilst the orientation had a passive linkage that carried the cutter on the end of the arm. This provides a low-cost small robotic system that is light and easy to use.

Fig. 2. The 5 axes trolley mounted robot with patient motion monitoring using a mechanical "Microscribe" arm.

3 axes (pitch, yaw and in/out) are powered, whilst the orientation device that carries the cutter on the end of the arm, is passive and configured to have a common centre of rotation at the centre of the ball cutter as shown in Fig. 3.

B. Planning System.

In order to fully utilize the potential accuracy of a robot, a planning system is required. This was based on a 3D CT scan of the patient leg to provide an accurate model on which to pre-operatively plan the procedure. A 3D image of the bones is provide that can be scaled, rotated to view from any direction and has variable transparency to show *quasi* x-ray views. Onto this the appropriate size and type of prosthesis can be overlaid and positioned until the desired amount of resection and alignment is achieved. A minimally invasive uni-condylar knee procedure was undertaken in which, instead of a total knee replacement (TKR), only one of the condyles is resurfaced using a prosthesis [6]. This requires a minimal removal of bone stock compared to TKR, and is a more challenging procedure conventionally, but is made simpler by the use of the robot.

Fig. 3. The passive orientation device showing the common center of rotation at the centre of the cutting ball.

C. Registration

At the start of the operative procedure, it is necessary to register the patient data and pre-operative plan to the current location of the patient and robot. This can be a major source of inaccuracy in the overall procedure. A modified form of Iterative Closest Point (ICP) algorithm was used. To minimize the time and help accuracy this was "bounded" by using the hip centre as a location. To locate this, the robot tip was connected to a pin located in the distal femur and the leg rotated through small angular excursions whilst the robot encoders collected the motion data to extrapolate the hip centre location and correlate with that found in the whole leg CT scan. A 1mm dia probe was then mounted on the cutter drive and used to touch onto the bone surface of the distal femur at a number of locations through a small skin access slit in the femur. This produces a cloud of points on the surface of the femur which can then be correlated with the surface obtained from the pre-operative CT image. The process is repeated separately for the proximal tibia. Both femur and tibia are separately monitored for leg motion throughout the

procedure by a single pin attached to the tip of the Microscribe arm. A 10 mm dia ball-ended cutter is used whilst the cutting process is observed on a computer display, since the cutter is out of sight down a small slit inside the skin. The display shows the cutting process as the bone is machined. When the desired level of cut is achieved, the screen color at that location turns green. The tibia is usually machined before the femur to allow more easy access to cut the rear of the femur.

III. DISCUSSION

Some systems e.g. Robodoc [7], are autonomous and once positioned at the site the sequence of cuts is automatic with no further involvement in the process from the surgeon than to hold an emergency off button. However, the author feels that a hands-on approach is more acceptable to the surgeon in which the surgeon is in direct control of the robot tool and initiates the sequence of cuts whilst monitoring progress. The use of Active Constraints also ensures that the robot provides accuracy and constraint, thus enhancing safety. However, it is also possible to have some autonomous processes in such a hands-on system, e.g., a small number of roughing cuts or repetitive motions that would otherwise tire the surgeon.

Whilst some orthopaedic robot systems target total hip or total knee replacement, it can be argued that these are procedures that the surgeon conventionally finds easy to do and the results are usually acceptable since the prostheses are said to be designed to be forgiving of placement error. For this reason, the author feels that minimally invasive procedures, such as uni-condylar knee replacement, are a better area for robotics since they are more challenging conventionally.

In order to ensure that the uni-condylar knee replacement procedure was correctly carried out, a small prospective randomized trial of around 30 patients was carried out to compare the robot results with those conventionally [2]. To ensure a similar process, both conventional and robotic patients had a pre-operative CT scan and a plan of what was to be attempted. Post operatively, all patients received a CT scan to compare achieved with planned results. All robotic patients were shown to have mechanical alignment of femur and tibia within 2 degrees, whilst of the conventional patients only 40% were within 2 degrees although the surgeons were all experienced in this conventional approach. The planning system was found to be of benefit, even by the conventional surgeons who had not previously used one.

IV. CONCLUSIONS

A robotic system for orthopaedic surgery joint replacement has been developed and tried clinically. The concept of Active Constraint robotic control has also seen application in a number of surgical robotic systems, including that of the EU project uRALP. The system uses a pre-operative 3D CT scan and is a rare example of a commercial surgical robot which utilizes 3D reconstruction, motion compensation, virtual guidance and haptic feedback. After 8 years of research at Imperial College London, the Acrobot Company was set up in 1999 to exploit this work and a cost effective surgical robotic system was produced commercially based on a trolley mounted robot arm carrying a high speed cutting burr. The Acrobot Company was acquired in 2010 by the Stanmore Implants Worldwide Ltd (SIW) [8]. Development of the system continued and a patient-specific uni-condylar prosthesis was realized that benefitted from the use of a robot to generate complex but accurate bone cuts [9]. SIW sold the Acrobot system to the American company MAKO in 2013 [10]. However, the author is of the opinion that this type of hands-on robot, in which the robot actively constrains the surgeon to an accurate and safe region, is a possible model for other medical robotic systems.

V. ACKNOWLEDGMENTS

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