MECHATRONIC ASSISTANCE FOR FEMORAL & TIBIAL OSTEOTOMIES

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Abstract. *The The aim of this research has been the development of a mechatronic system to assist orthopaedic surgeons in closing wedge osteotomy procedures around the knee joint, with the aim to improve the accuracy and repeatability of such procedures. Osteotomy procedures around the knee joint, involve the cutting, realignment and subsequent stabilisation of either the tibia or the femur. These procedures are carried out with the view to relieving the pain associated with chronic osteoarthritis or correcting a lower limb deformity or correction of a misaligned fracture. Typically, such procedures involve the removal of a wedge-shaped piece of bone, followed by closure and internal fixation of the osteotomy site. Unfortunately, the subjective nature of the preoperative planning and free-hand surgical techniques currently employed can lead to significant outcome variability and high complication rates. A prototype computer-robotic system has been developed. It is intended to perform automated cutting of the osteotomy planes under surgeon supervision. It is aimed particularly at correcting complex multi-plane deformities that are difficult with conventional techniques. A system which supports quantitative 3-D preoperative planning of a tibial/femoral osteotomy procedure, followed by precise robotic execution of the planned resections, could potentially lead to significant improvements upon the accuracy and repeatability of existing freehand surgical techniques.*

Keywords*: osteotomy, computer assisted surgery, medical robotics*

1. Introduction

The aim of this research has been the development of a mechatronic system to assist orthopaedic surgeons in closing wedge osteotomy procedures around the knee joint, with the aim to improve the accuracy and repeatability of such procedures.

Osteotomy procedures around the knee joint, involve the cutting, realignment and subsequent stabilisation of either the tibia or the femur. These procedures are carried out with the view to relieving the pain associated with chronic osteoarthritis or correcting a lower limb deformity or correction of a misaligned fracture. An example of closing wedge proximal tibial osteotomy for correction of varus deformity is shown in Fig. 1. Typically, such procedures involve the removal of a wedge-shaped piece of bone, followed by closure and internal fixation of the osteotomy site. Unfortunately, the subjective nature of the preoperative planning and free-hand surgical techniques currently employed can lead to significant outcome variability and high complication rates (Insall, 1984, Berman, 1991, Coventry, 1993, Rinonapoli, 1998). The considerable scope for error associated with the free-hand wedge removal process gives the most grounds for concern (Insall, 1993). Postoperative results display significant outcome variability, with both over-correction and under-correction being observed, in relation to the accuracy of knee joint re-alignment. As a result, complications such as delayed/non-union of the osteotomy site, intra-articular fractures, or even the recurrence of deformity and pain in the longer-term, are not uncommon. Paley (1994) therefore conclude that the joint goals of meticulous planning and precise execution must be adopted with a view to producing a longer-lasting osteotomy. Hence, the surgical aim of this project is to improve the planning, implementation and outcome of osteotomy procedures.

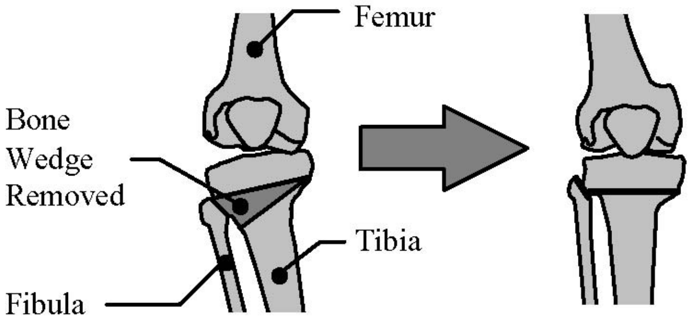

Figure 1: A closing wedge proximal tibial osteotomy.

A prototype computer-robotic system has been developed. It is intended to perform automated cutting of the osteotomy planes under surgeon supervision. It is aimed particularly at correcting complex multi-plane deformities that are difficult with conventional techniques. A system which supports quantitative 3-D preoperative planning of a tibial/femoral osteotomy procedure, followed by precise robotic execution of the planned resections, could potentially lead to significant improvements upon the accuracy and repeatability of existing freehand surgical techniques. The computer-robotic system which has been developed consists of a custom-built “fail-safe” six degree-of-freedom surgical robot, with an instrumented saw driver unit, and a computer based planning system. It is aimed to:

Assist surgeons in accurate planning, including multiple-plane deformities which are difficult to correct with conventional two-dimensional planning approaches.

Aid in accurate implementation of a pre-planned surgical procedure to obtain a good outcome for the patient.

Provide improved visual feedback to the surgeon during the surgical procedure, by continuously displaying the position of the osteotomy saw relative to the bone.

2. Mechatronic Assisted Osteotomy

A diagram of the the overall system is shown in Fig. 2. The overall procedure involves a planning and implemention stages. This entails a pre-operative surgical procedure planning, datuming of the robot to the bone intra-operatively, robot control and bone cutting, and monitoring of the robot end-effector and the bone cutting process.

2.1 Pre-operative Planning

The planning of the surgical operation is carried out first, before the surgical procedure takes place, using 3-D models of bone obtained from CT scans, or using a combination of pre-operative planar x-ray films. The surgeon has the ability at this stage to interactively place and adjust the osteotomy wedge and to simulate and visualise the outcome of the operation. The final position and orientation of the wedge is stored and used in the operating theatre to produce the required saw cuts.

2.2 Trajectory Planning and Implementation

In theatre, depending upon which leg is to be operated on, and whether a distal femoral or a proximal tibial osteotomy is to be performed, the robotic system will be moved to the appropriate side of the operating table. The patient’s leg is also flexed to approximately a ninety degree angle and secured to an immobilisation device. X-ray images of the patient’s leg are then acquired using a fluoroscopic image-intensifier. This is necessary to provide sufficient information for datuming the bone to pre-operative images, and thus producing the required saw cuts which are downloaded to the robot controller. The registration of the robot end-effector (i.e. the saw) to the bone and the provision of the cutting trajectories are provided using a "computer based planning system". The intra-operative registration is established via the use of a real-time opto-electronic position measurement system which is able to track infra-red LEDs mounted on rigid bodies attached to the robot, patient/immobilisation device, and to the intra-operative C-arm fluoroscopy unit. A surface-based registration technique, which employs anatomical landmarks to perform the matching process, is used to register preoperative and intra-operative images/bone models.

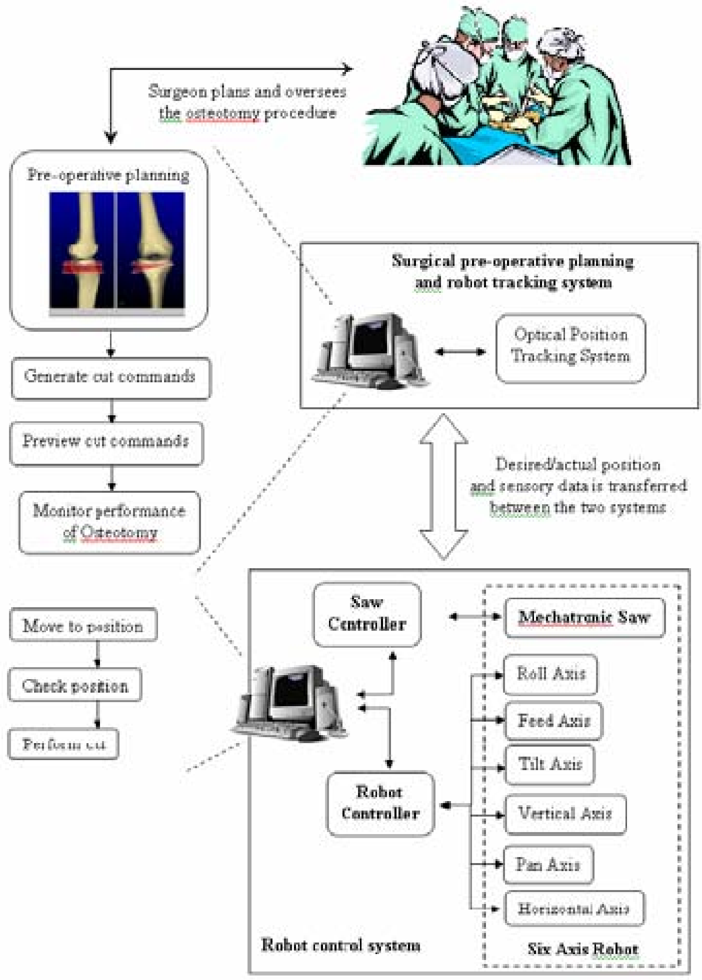

Figure 2: Mechatronic Assisted Osteotomy.

The computer based planning system produces a set of transformations for the desired positions and orientations of the saw. Inverse kinematics is then performed to provide the necessary link motions and move the saw to the desired pose which is independently checked using the optical tracking system. Any errors are therefore automatically compensated for. Once the saw is positioned along the desired cut, sawing is initiated by the surgeon, and the position of the saw with respect to the bone is continuously monitored. The sawing/cutting force is also continuously measured and used for both safety (to ensure that the saw does not cut soft tissue) and to confirm/adjust the saw position with respect to the bone.

The saw positioning process is performed by the robotic system in two distinct phases: "Coarse" passive alignment (using a floor-standing passive manipulator) to locate the robot at the operative site, and "fine" active alignment (using the custom-built active manipulator) for each cut. Hence, the robotic sub-system is composed of an active saw-deployment robot mounted on a braked, floor-standing, passive positioning system. The passive system allows the surgical team to manually locate, under computer control, the active robot at the operative site, and to subsequently maintain this pose throughout the surgical procedure. This, has allowed the use of a lighter more compact design, whilst at the same time avoiding the large active motions associated with anthropomorphic robots.

3. Custom-built Surgical Robot

A Custom-Built 6 degrees-of-freedom (DOF) robot has been developed as part of this research. The use of an industrial robot is perfectly acceptable in the context of a laboratory-based demonstration system, but the large working volume and reach associated with such robots create significant problems in relation to the intraoperative safety of the patient and the surgical team. A more direct development route, involving the design and manufacture of a custom-built robotic manipulator has therefore been followed in relation to the Osteotomy Robot. The custom-built robot has 3 prismatic joints (horizontal, vertical and feed actuators) and 3 revolute joints (Pan, tilt and roll actuators). The robot has been designed to fail-hard, i.e. should the power to the joints fail for whatever reason all the joints will remain in their current position. The actuator mechanisms for all the joints, except for the roll joint, have been designed to be non-backdriveable, and a specifically designed electromechanical brake with zero-backlash has been used for the roll joint. The latter design for the roll joint was necessary to keep the size to a minimum.

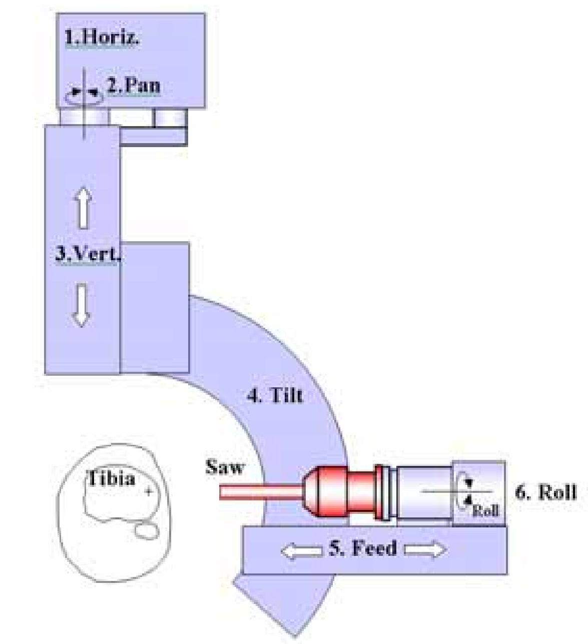

Figure.3: Kinematic configuration of the active manipulator

Different kinematic configurations for the active saw-positioning robot were investigated in line with the design requirements. The kinematic configuration which has been chosen ensures that the rotation axes are located in the optimum positions with respect to the femur/tibia, thereby significantly reducing the necessary linear motions and the overall size/weight of the robot. For example, the tilt rotation, which controls the angle-of-attack of the saw blades into the femur/tibia, is implemented by mounting the feed unit on a circular motion guide (arc-shaped rail). When the centre of the arc is correctly positioned, using the passive “coarse” alignment and the active robot’s linear degrees-of-freedom, the saw can therefore be safely rotated around a point within the femur/tibia.

4. Instrumented Saw

The instrumented “smart” saw driver unit has been custom-built to provide enhanced bone cutting performance and to minimise bone cutting induced vibrations. The unit employs a double bladed configuration such that the cutting forces generated by one blade are always counteracted by the opposing blade, thereby significantly reducing the forces transmitted to the robot. The feed rate of the robot’s end-effector can be adjusted according to cutting conditions, as measured by the “smart” saw. Also, preliminary test results have shown that the surface finish of bone cuts produced with the “smart” saw driver are at least as good as those obtained with conventional oscillating saws.

It was decided to develop a ‘smart’ saw because existing traditional sagittal saws do not have the necessary instrumentation, the cutting profile is not optimum and the induced vibration is not desirable. As the blade approaches the end of the cut, the corners of the blade for the existing saws would inevitably protrude beyond the edge of the bone into the surrounding soft tissues, therefore a continuous change in orientation would be necessary for such saws to follow the bone contour. Ideally, the shape of the locus described by the blade would be configured in a small circle, not in a shallow arc like the sagittal saw, allowing the blade to cut right to the edge of the bone with a minimum of protrusion. Another disadvantage of the sagittal saw, for robotic applications is that the single bladed design generates substantial vibration and jerkiness in use. Moctezuma (1997) eliminated this by fitting two blades, operating 180° out of phase with each other, thus balancing vibratory and cutting forces. Therefore, in order to achieve the desired fit between the saw blade and the bone, and to provide a balanced and vibration free end-effector, a double bladed design, with blades driven in circular (or elliptical) orbit was developed. Also, to ensure that the saw is not fed beyond the edge of the bone into the surrounding soft tissues it is equipped with sensors to measure feed force, and to minimise the risk of thermal osteonecrosis the blades of the saw are equipped with thermocouples which measure the temperature at the cutting face.

5. Discussion

A computer and robotic assisted surgery system, designed to aid the surgeon in performing more accurate planning and implementation of osteotomy procedures around the knee has been described.

As discussed above, the shortcomings and scope for error associated with existing osteotomy techniques make the postoperative results somewhat unpredictable, and there is evidence that the long-term success of an osteotomy procedure is directly related to surgical precision. A number of computer-assisted surgery applications have therefore been developed with the aim of improving upon the results obtained using existing surgical techniques. However, computer-assisted surgery systems all suffer from an inherent limitation, in that the invasive stage of the surgical intervention is still performed by hand, thereby leaving scope for human error. Automation of the bone cutting process, via robotic-assistance, has therefore been advocated during the current investigation with the aim of maximising intraoperative precision.

The use of a fully powered autonomous robot to perform (hip joint) osteotomy procedures has previously been investigated by Moctezuma (1994). A commercially available clean room robot (PUMA 560) was used. However, Moctezuma. acknowledged that an industrial robot cannot be used in a clinical environment due to the high security standards Moctezuma (1997). It is for this reason that a custom-built robotic system has been developed.

Laboratory tests have been carried out. The two main tasks that have been evaluated include the integration of the different components of the overall system, and the accuracy of simulated surgical procedures. The performance specifications specified by the collaborating surgeons have been met.

Although the robotic system developed in this research is still at an early stage of development, a preliminary evaluation has demonstrated that the system's robotic components satisfy the relevant clinical and engineering performance requirements. Tests involving the "smart" saw driver unit also continue to suggests that improved cutting performance can be obtained via sensory feedback and feed rate control. Further development of the preoperative planning and simulation system, along with in-depth evaluations of the clinical aspects of the patient-to-robot immobilisation and the surgical sterility compliance problems, are therefore warranted in order to demonstrate the full potential of the system as a whole.

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