Design of a Parallel Long Bone Fracture Reduction Robot with Planning Treatment Tool

A. E. Graham, S. Q. Xie and K. C. Aw.  
Department of Mechanical Engineering  
The University of Auckland  
Auckland, New Zealand  
agra036@ec.auckland.ac.nz

W. L. Xu  
Institute of Technology and Engineering  
Massey University  
Auckland, New Zealand

S. Mukherjee  
Department of Orthopaedic Surgery  
Palmerston North Hospital  
Palmerston North, New Zealand

Abstract - The principals and procedure of long bone surgery are presented and the need for robotic assistance is established. Existing problems include radiation exposure from fluoroscopy, mental strain from reconstructing 3 dimensional images and physical fatigue from overcoming fracture deforming forces. These problems are addressed by a proposed fracture reduction robot which aids in treatment planning and reduction of the fracture. A Flexible Parallel Robot (FleP) with an active force/position controller is designed to perform the operation. A Computer-Aided Planning Treatment Tool (CAPTT) provides image analysis, path planning and simulation. An Advanced Human Machine Interface (AHMI) attempts to provide a companion feeling between robot and surgeon by using human forms of communication. The result is a reduction in radiation exposure, removal of the need to reconstruct images mentally and there is no longer any physical strain.

Index Terms - robotic surgery, computer assisted surgery, robot control, active robots.

I. INTRODUCTION

Medical Robotics and Computer Assisted Surgery (CAS) are emerging fields that can potentially provide many benefits to patients and surgeons. There is also an increasing demand for highly complex and precise procedures to be carried out that require the surgeon to have new methods and tools to undertake. It is through the integration of modern technologies developed in surgery, image processing, control and artificial intelligence that will revolutionise the way in which modern and future surgery will be performed.

Computer-aided robot assisted platforms have the ability to make use of modern sensor technologies, new mechanical systems, and the rapid advancing computer software and hardware technologies. They can provide a surgeon with in-depth data analysis, precise and planned control and unique visualisation methods. This kind of platform increases surgical accuracy, reduces hand tremor, and enables data analysis to aid follow up treatment. Other advantages of such a platform also include an improvement in safety, remote operation, and saving in costs.

Orthopaedic surgery has been one of the fields to benefit significantly from medical robotics so far with hip replacement, spine surgery, knee surgery and fracture treatment all seeing systems being developed such as in [1], [2], [3], and [4], respectively. For these to be effective and accepted by the medical field they need to have an adequate learning curve, increase the performance, and reduce the time and cost of surgery. This is achieved by developing novel control strategies that are intuitive and robust. Sensors are used for redundancy and safety during both assisted and automated procedures. The creation of new types of robots that are ideally suited for the operating room (OR) environment. These are able to operate in close proximity and interactively with people while using a limited amount of valuable OR floor space.

Several systems have seen use in clinical environments such as Robodoc for total hip replacement [1] and da Vinci for minimally invasive surgery (MIS) [5]. However as systems become ambitious there are areas that hamper the implementation and development of medical robotics. The lack of an agreed safety standard slows development due to legal and liability problems. The majority of the robotic and CAS platforms developed are very specific in their purpose, allowing only a single, or part of, a specific procedure to be performed. Imaging methods are often slow or impractical for the medical procedure and need to be improved to allow better and more accurate planning, registration and navigation. Feedback to the surgeon through force or haptic devices along with all new manipulator designs are required to allow the surgeon to ‘feel’ what is happening. New control strategies should be developed for precise and functional control of robotic systems. Methods to integrate the surgeon as part of the control loop and allow systems to become more autonomous, precise and reliable in operation need to be implemented. These ideas will lead to the development of a new medical robot system for long bone fracture reduction.

This paper is structured as follows. Section II. presents the fracture reduction procedure and establishes the need for a medical robotic system. Section III. details the design and components of the robotic system, while Section IV. draws conclusions.

II. FRACTURE REDUCTION PROCEDURE

Medical robotics look set to play an important part in the future of surgical treatment. Long bone fractures are comprised largely of rigid components and as such are well suited to the application of robotics [6, 7]. The long bones are those such as the tibia and femur located in humans lower extremities where the nature of them means they are
commonly fractured. In persons aged 1 to 34 accidental injury is the most common cause of death and in adults over 65, 87% of falls result in a fracture [8]. The principals behind the treatment of fractures and the procedure are important to understand so the need for a medical robotic system can be identified.

A) Principals of Surgical Treatment of Fractures

Reference [9] gave four principals of surgical treatment of fractures that are as applicable today as they were in the 1700s. Based on these principals the Association for the Study of Internal Fixation (AO-ASIF) formulated four treatment guidelines [8]. These are anatomical reduction, stable internal fixation, preservation of blood supply, and active pain free mobilisation of the adjacent muscles. Examining the current method for applying these principals results in the following descriptions of the guidelines.

1) Exposure of the fracture. Surgical exposure is needed to develop a 3D perspective of the fracture configuration, its attached soft tissue and its degree of multiplanar displacement. An image intensifier allows surgical approaches without soft tissue dissection.

2) Reduction of the fracture. Once anatomy and mechanics are understood, recreating the deforming force and realigning the fracture with traction often results in reduction. First adequate alignment of the bone in anteroposterior and mediolateral planes to avoid abnormal load deformations on weight bearing joints. Second rotation of the axis should be corrected to be close as possible to that of the normal extremity.

3) Provisional stability of the fracture. The fracture is temporarily stabilised by an internal device or externally by wires, screws or pins

4) Definitive stabilisation of the fracture. Obtain mechanical stability dictated by the pre-operative plan. The mechanical construct must have sufficient fatigue life and allow pain free motion of adjacent joints and muscle tendons. The fixation should also permit some load sharing so it does not impair the regeneration of bone.

B) Procedure

The definition of fracture reduction is to reposition bone fragments in correct alignment. There are two types, closed reduction where the bone is set without making an incision in the skin and open reduction involving cutting through the skin to realign the bones. The goal in both is to achieve union in the most anatomical position, while minimising soft tissue damage. A reduction is done to return a broken bone to its proper alignment. This is done for the following reasons. 1) The bone can heal correctly and quickly. 2) To decrease pain and prevent later deformity. 3) To allow the patient to regain use of the bone and limb.

Fig. 1, shows the steps required for the fracture treatment procedure. Prior to the procedure the physician will perform a physical exam, have X-rays taken of the fracture and generally provide a splint for the broken bone to reduce the risk of further injury. The physical exam and x-rays are used to classify the fracture and tissue damage and evaluate the patient. A treatment plan is then formed to specifically meet the needs of each patient with the planned goal to have a high chance resulting in healing of soft tissue and bone with the fewest complications.

Open reduction method is used if the bone is fragmented or difficult to reduce, and may require screws and a plate to hold the fragments in place. The surgeon makes a cut in the skin covering the break to expose the bone fragments. The bone fragments are moved into their normal position and a fixture is used to hold the realigned bones in place. In closed reduction the surgeon manipulates the bone fragments into their normal position by applying traction and uses a cast or splint to hold them in place. There is no incision. Fluoroscopy images are readily available in the OR and are used to visualise the fracture. This is done continuously throughout the alignment procedure and the fixation task as needed.

C) Need for Computer Assistance and Medical Robotics

Large multinational companies have now formed focused on the treatment of fractures to meet patient’s high expectations; however the choice of fracture treatment is still not clear cut due to the options available. Reference [10] suggested there have been 4 eras to fracture treatment. These eras have been defined by the development of medical treatments procedures. They began at pre-antiseptic with a high mortality of 38.5%. Currently the field is in Era 4 which has been to preserve function of the limb. Robotic systems show a lot of potential here to advance the field again.

A robotic system is needed to address many of the problems associated with the existing procedure. Mental reconstruction of uncorrelated fluoroscopy images can be demanding for the surgeon, computer assistance can take these images and replace them with a virtual 3 dimensional (3D) view for the surgeon allowing excellent visualisation. Radiation exposure can be dramatically reduced while the robot carries out the motion. Currently a fracture treatment procedure may result in up to 30 minutes of exposure to fluoroscopy; each minute produces 4 rads of radiation, giving a total of 120 rads. 100 rads may cause nausea and vomiting for 1-2 days and a temporary drop in production of new blood.
cells while 350 rads can cause nausea and vomiting initially, followed by a period of apparent wellness. At 3-4 weeks, there is a potential for deficiency of white blood cells and platelets, resulting in the need for medical treatment. Fatigue is also often a problem for OR staff, especially during the reduction process. Up to 240N of force can be required to counter the deforming muscle and tendons [11], this can be strenuous especially after long hours at work.

Meeting patient expectation to be treated quickly for healing speed and have excellent alignment achieved for cosmetic reasons are also areas that can be addressed by medical robotics. The primary goal of union can be achieved through the development of enhanced imaging technologies and path planning, while the robot is moved under a controlled force. Pre-operative planning software can perform analysis on stresses applied to the extremity and be used to plan the method of fixation, it can also help determine the placement of provisional stabilisation. This currently requires careful planning so it will not interfere with the definitive fixation. Robot assistance can potentially reduce the skill required by the surgeon and the number of staff required allowing more people to receive expert treatment earlier. This has already shown to reduce the length of hospital stays. Logging of data and automatic analysis can help the assessment procedure, if a suboptimal assessment is made the robotic system can have measures to detect this in surgery and provide mechanism to re-plan. For example morel-lavellée syndrome where fascia is separated from the skin is frequently over looked. By analysis of the forces and motions during reduction this can potentially be diagnosed. It is likely that with the introduction and increasing use of robotics in hospitals that a new era of advanced treatment is about to begin.

III. PROPOSED FRACTURE REDUCTION ROBOT

There are four main areas that can benefit from medical robotics in fracture reduction. Planning, reducing the fracture, providing fixation, and follow-up. A new generation of robotic system is proposed as shown in Fig. 2. The system includes the Flexible Parallel Robot (FleP), Computer-Aided Planning Treatment Tool (CAPTT), and an Advanced Human-Machine Interface (AHMI). FleP is designed as a purpose built medical robot that has capabilities to carry out the long bone reduction process with an amount of intrinsic safety. FleP goes a step further from many existing medical robotic systems [1-3, 6, 12]. to be more flexible allowing its use in many procedures with interchangeable end-effecters. Its control system is proposed to use both force and position information to allow it to correctly interact with its environment. CAPPT is used for assisting and planning the operation and analysis. The aim of this is to aid diagnosis and reduce the time required to plan the procedure. Capabilities provided for tracking surgical outcomes will allow more knowledge to be gained over time and increase the performance of surgery. AHMI ensures the procedure is carried out with co-operation between the surgeon and FleP. Natural forms of human communication are proposed including vocal and augmented reality (AR) ensures the surgeon's attention is always focused on the operation.

CAS systems such as FRACAS [4], are addressing some of the visualisation and planning stages however there is still much work to be done. Such systems also require computer tomography (CT) scans which are not typically needed adding time and cost to the procedure. What is proposed below is a novel approach for reducing the fracture using existing imaging technology in hospitals. This ensures the system will easily fit in and assimilate with the current procedures. Reduction accommodates robotic functions better than the fixation as fixation methods are highly variable. They depend on the situation and a patient is better treated by a surgeon in this case who has extreme flexibility and superior judgement.

A. Flexible Parallel Robot (FleP)

FleP will replace the existing reduction device seen in Fig. 3. This traction machine has low accuracy and can provide force in a singular axis resulting in difficult realignment. As can be seen the proximity also results in radiation exposure to the surgeon. The FleP structure presents a number of challenges requiring both translation and rotation while being small to conserve OR floor space and lightweight to easily transport. A modular parallel robot will be developed to fit this purpose. Table I. summarises the advantages of a parallel mechanism in this situation over a serial mechanism. This choice is further supported in several recent resources from literature that parallel robots are ideally suited to medical applications [13-15]. This kind of configuration allows for an accurate robot that can meet the force requirement of 240 N while being compact to fit in with existing system. It provides 6 Degrees of Freedom (DOF) which can sufficiently correct alignment in anteroposterior and mediolateral planes as well as correcting any malrotation. The top plate of the parallel mechanism will be modular, allowing attachments of multiple kinds of end effecters to
perform different medical procedures. In this long bone reduction application a foot holster similar to what is shown in Fig. 3, will be attached. The work envelop will be carefully considered to meet the requirements of both functionality and safety.

In long bone reduction FleP must interact with its environment performing pulling and twisting. Implementation of these tasks intrinsically requires that the robot be able to realise a controlled force to overcome or comply with the environment as well as position locations. In this way the best anatomical union can be achieved, while overcoming the deforming forces and minimising damage to soft tissue. Examining the reduction of the femur which is one of the most commonly fractured bones and the largest, there will be soft tissue attached. The fracture is surrounded by large powerful muscles that exert angular and deforming forces on the fracture site. Fig. 4, shows the muscles and the action produced on the bone. The proximal fragment is pulled towards an abducted position by the gluteal muscles while being rotated by the iliopsoas. The adductors seen spanning the length of the femur produce an adduction force to the distal fragment, especially in the case of a midshaft fracture by causing axial and varus pull. For a fracture that runs through the supracondylar area, angular rotation will also be caused by the gastrocnemius. As can be seen, depending on the location and classification of the fracture, resulting deformity and forces can be highly complex, however these can be predicted from the nature of the fracture and need to be taken into account when designing a controller. Incorrect axial alignment and malrotation may lead to shortening, cosmetic damage and stress loading of other joints all leading towards posttraumatic arthritis. Modelling, understanding, and control method are all technical challenges here to be solved.

An active force/position control algorithm is proposed to control movement of the robot under supervision of the surgeon. The active approach is taken as opposed to a semi-active or passive so the surgeon can be located away from the c-arm device (source of radiation). Additionally, it is proposed that active robotic systems will become more attractive as safety requirements are met and FleP is to be designed to meet the requirements of the next generation. The algorithm will use both position and force information to carry out pulling and twisting. This will fulfil the intrinsic requirements of the task with soft tissue, muscle and ligaments attached. The control method will be adaptive enough to function under the various types of situations and fractures encountered, such as shaft, distal and proximal.

B) Computer-Aided Planning Treatment Tool (CAPTT)

To assist in planning the procedure a CAPTT will be developed. This tool includes modules to reconstruct 3D information from medical images and perform path planning. It contains databases of information about fractures, fixation devices and prosthesis, and has simulation and analysis functions.

The reconstructed 3D information of bones is a major feature of the CAPTT. This will identify and register the location of the bones to the robot and patient. Fluoroscopy registration of bones is initially used as this is a non-invasive,
fiducial free technique using equipment that is already available in hospitals. Current popular use of fiducials for registration are invasive and there have been several accounts of these causing patient discomfort and pain after surgery [17, 18]. Fiducials also increase pre-operative time as they need to be attached before imaging takes place. Fluoroscopy images are however low contrast and depth is hard to control, the difficulty is increased by bone fragments that overlap during fracture. Once the bones are registered the relative displacement in translation and rotation are determined. This information can then be accessed by other components such as the control system and AHMI.

Path planning is a challenge involving knowledge and models about anatomical behaviour being combined with the patient specific plan developed. Elderly patients for example who have a high risk of cardiac, pulmonary and psychiatric co-morbidities may be at risk from suffering from morbidity or mortality. If the CAPTT can help plan and carry out the patient specific reduction in a tender manner the surgeon may be able to reduce the need for open reduction and use lower doses of anaesthetics.

The CAPTT contains databases of information about fractures, fixation devices and prosthesis. This allows the CAPTT to provide fracture classification and a treatment plan which the surgeon can edit if needed during pre-operative stages. The databases are easily modified to add additional procedures as the field advances. Currently there is no way to have quantitative analysis of outcomes and few methods to assess the success of surgery. A key benefit of the database is that it allows post-operative and pre-operative information to be stored and used to update future planning procedures and assist patient follow-up. Once the fracture is classified and the surgeon is happy with the general procedure plan the location of a provisional fixation will be calculated and selected that does not interfere with the definitive fixation. This will be an automatic procedure based on a set of rules and information obtained from previous operations contained within the CAPTT. Positions will be displayed on a 3D model for inspection and verification, allowing modification if necessary. Prosthesis, if required along with fixation can be attached before imaging takes place. Fluoroscopy images are needed and aid in any manual procedure that is to be carried out such as the existing intramedullary screw placement. Here an artificial overlay of the bone locations can be placed on the patient and progress of the drilling procedure is shown without further fluoroscopy needed.

D) Safety Features

From a safety perspective it is hard to determine requirements until they have been decided by the wider medical community and agreed on. Suggestions for making a safe medical have been made in [20]. Similar measures have been used and gained a few systems clinical trials and commercial sales. These typical safety features such as a watchdog timer, dead-man switch, force monitoring, encoder redundancy and software motion limits will be incorporated into the design. This system will also prescribe to the theory that medical robotics should be purposely built for intrinsic safety. Using a parallel mechanism and knowing the relation between actuator extension and position will provide some amount of indirect redundancy as the actuators extensions are coupled.

IV. CONCLUSIONS

Long bone fractures are a very common injury, especially in the lower extremities. The principal of fracture reduction is to achieve the best anatomic union by means of reduction and fixation. The current procedure can have significant exposure of radiation from fluoroscopy scans to OR staff, the surgeon is further mentally challenged to reconstruct 3D views from these scans, and physically reducing the fracture can be very fatiguing. Patient’s expectations are also increasing as they want fast, expert treatment.

This paper has proposed a robotic system to address these issues. FleP is a flexible parallel robot designed for long bone reduction. Its structure provides highly accurate movements in 6DOF and changeable end-effecters allow FleP to be used.
in a number of procedures. An active force/position control system is used for safe interaction with the environment where pulling and twisting motions are required. A computer-aided planning treatment tool CAPTT is proposed that will assist the surgeon in all areas pre-operative planning and allow data to be logged for follow-up. The surgeon co-operates with the system during operation through the AHMI interface, this uses voice communication and an AR display.

The benefits of using the proposed system include the following. For the surgeon, reduced exposure to radiation, removes the need to mentally reconstruct 3D images, and there is no fatigue as the reduction is carried out by the robot. The patient receives fast treatment as planning speed is increased while the chance of misdiagnosis is reduced through the aid of the planning tool and sensors. Improvements over other medical robotic systems are the fluoroscopy registration that is fiducial free avoiding patient discomfort, active control is used with the future processes in mind and human forms of communication are incorporated to help acceptance.

REFERENCES