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Parallel Manipulator Robot Assisted Femoral Fracture Reduction on Traction Table

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Abstract—**The principle of femoral shaft fracture reduction is to restore its pre-fractured limb length and mechanical axis. The current documented treatment method with traction table reduction does not conform to the quantitative alignment and reduction. There is also a great amount of X-Ray radiation exposure to both surgeon and patient during the procedure. For this reason, we introduced an innovated Parallel Manipulator Robot (PMR) application: A Femoral Shaft Fracture Reduction with Parallel Manipulator Robot on Traction Table. With this application, the quantitative control on fracture reduction and alignment can be achieved and the radiation exposure to both surgeons and patients can be greatly reduced.**

Index Terms—**femoral fracture reduction, Parallel Manipulator Robot, Stewart Platform, traction table, Computer Assisted Orthopedic Surgery, Taylor Spatial Frame, external fixation**

I. INTRODUCTION

FRACTURE reduction of femoral shaft fracture is the frequently operated orthopedic surgeries. The purpose of treating femoral shaft fracture is to stabilize the fractured femur for fast healing so as to return to the early mobility and function by means of fracture fixation [1]-[3]. Conventional surgical technique for the femoral fracture reduction is to place such patient in supine position on traction table and secured by the fasten belts. Attached to the traction frame is an adaptable stirrup. The fractured limb is flexed at the knee with the patella to the top. With wires and pins, this stirrup is secured on the distal segment of fractured femur. Aided by the C-Arm X-Ray, the surgeon can pull the overlapped femoral segments with the adaptable stirrup by turning the knob on traction frame. When proper traction is achieved, the surgeons will manually carry out adduction until the fracture is considered to be reduced anatomically, in both AP and ML views [4]. However, the manual reduction of femoral fracture has no quantitative control in terms of restoration of pre-fracture mechanical axis and limb length. To overcome the manual reduction shortcomings, several investigators have reported their approaches to achieve better results for femoral fracture reduction. In 2000, R. Hofstetter et al. published a paper [5] for applying Opto-electronic Navigation system to aid the femoral shaft fracture reduction. In this paper, they reported that they were using bi-planar C-Arm X-Ray images combining with Opto-electronic marker to achieve the alignment and reduction of experimental fractured bone model. However, they did not describe the way how the bone segments are being attached and moved together [6][7]. In 2005, T.M. Wang of BUAA et al of China [8] reported their development in computer assisted and image guided long bone fracture reduction device in a patent publication. The system they developed took series of bi-planar C-Arm X-Ray images longitudinally and stitched them together to obtain the full length long bone images of AP and ML views. Applying the image processing algorithm, the target length of the long bone can be obtained. With developed device, they can precisely restore the fractured long bone to pre-fractured length. Application of Parallel Manipulator Robot (PMR) opened a brand new opportunities for long bone fracture reduction in both traction and alignment management [9]-[12]. In orthopedic surgery, the Taylor Spatial Frame (TSF) played active role in deformity correction treatment. The utilization of TSF is based on the concept of PMR. Through adjusting the lengths of its six struts accordingly, the TSF can achieve fracture alignment and reduction by the 6 DOF movements of proximal and distal platforms attached to both sides of fractured bone segments secured by pins and wires [13]. In our research, we implemented PMR on traction table for femoral fracture reduction in clinical environment. In the following sections we described in depth for our implementation.

II. METHODS

A. Parallel Manipulator Robot on Traction Table

The PMR is assembled with one platform being a 2/3 circular ring and another being a solid disk. In between there are six motor driven struts, or actuators, connecting the two platforms, following the rule of standard Stewart platform structure. The patient is placed in a supine position on the traction table. The solid disk side of PMR is attached to the central pole of standard traction table by the boot adaptor. The fractured femur is flexed at the knee with patella to the top. The 2/3 circular ring, with 1/3 open circle down, fixed to the fractured distal femur with one trans-wire and one self-taping screw, acting as adaptable stirrup fixing scheme. On the proximal femur of patient, the fixation is applied to the traction table, either by pin fixations or by fastening belt, as shown in Fig. 1. In this configuration, the solid disk side of PMR and the proximal femur of the patient can be

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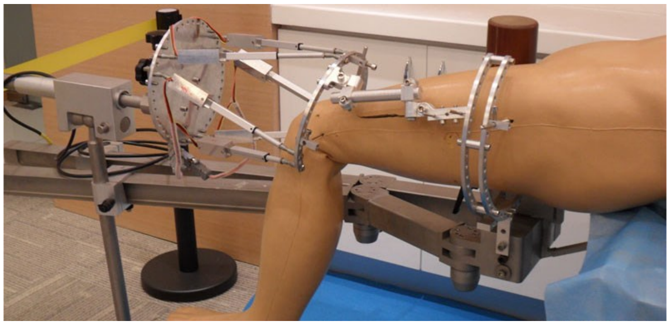


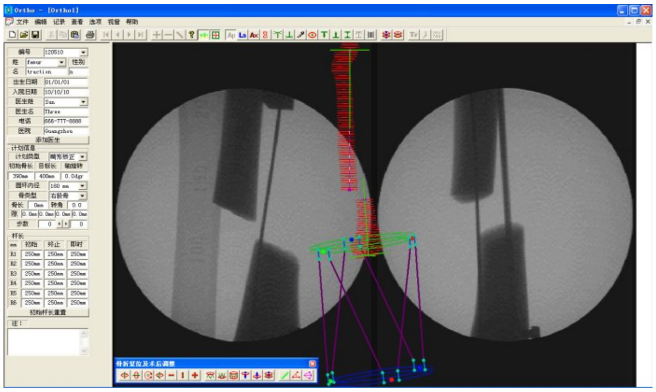
Fig. 1 Parallel Manipulator Robot on Traction Table

treated as one rigid body or quasi-rigid body. The distal femur, fixed to the 2/3 circular ring platform, will perform the 6 DOF movement. The alignment and reduction algorithm is based on the restoring the pre-fractured limb length and mechanical axis principle.

B. Femoral Shaft Fracture Reduction Planning

Four 3D models of normal lower limbs were created for use. They are left tibia, left femur, right tibia, and right femur, in the assumption that all human femur/tibia are similar in shape, except for length and size. Prior to perform the reduction planning, the healthy side of the limb will be C-Arm X-Rayed on distal and proximal joints with ruler to determine pre-fractured limb length. On fractured side, both AP and ML C-Arm X-Ray need to be taken at fracture site for the consideration of oblique displacement and angulations of fracture. At this time, a ruler is also placed at the scene. Ruler marker within X-Ray images is used for the determination of fracture level and scaling factor between 3D bone model and background X-Ray image of planning software. The planning program will use the X-Ray images of AP and ML views of fractured femoral shaft as the background image. The target length of fractured femur is specified. Then available 3D model of right type of bone segment is selected and imported into the program. After the 3D model is scaled, the fracture simulation is performed on the selected 3D bone model at the level indicated by ruler image, as Fig. 2.

With mobile platform of 3D PMR placed on distal side of fractured femur as moving objects, the base platform of PMR and proximal side of fractured femoral shaft remained as unmoving objects. Superimposed onto the background X-Ray images, both fractured bone segments and mobile platform of PMR are aligned in AP and ML views.



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计划类型 畸形矫正
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mm	初始	终止	即时
B1	250mm	250mm	250mm
B2	250mm	250mm	250mm
B3	250mm	250mm	250mm
B4	250mm	250mm	250mm
B5	250mm	250mm	250mm
B6	250mm	250mm	250mm

初始杆长重置
注：

Fig. 2 Fracture Reduction Simulator

After the assumed mechanical axes of proximal and distal fragments are aligned with mobile platform of PMR, a table of length changes for 6 motor driven struts is created, which described the instant length for each of 6 struts in the course of alignment and reduction. It is this flow of data that is used for driving the 6 motor driven struts to perform the 2/3 circular ring's 6 DOF movement so as to achieve the distal femur alignment and reduction to proximal femur, as the result, to restore the pre-fractured limb length and mechanical axis.

C. Stewart Platform

The PMR is one form of Stewart Platform structure. It has some advantages over its counterpart, the Serial Manipulator Robot (SMR) in high rigidity, high accuracy and high load-carrying capacity [14]. The PMR used in this application is a 6-6 Spherical -Prismatic- Spherical (SPS) Stewart Platform. However, its spherical joints were replaced with the flexible universal joints - patent # CN102102712A, for the purpose of cushioning the hard collision between the fractured segments in the course of reduction.

Femoral fracture reduction with PMR involves both forward and inverse kinematics. Prior to installation and attachment of the PMR onto the fractured femur, the actuators of the PMR need to be initialized for proper length based on the reduction planning. This process needs forward kinematics solution of PMR. When performing the femoral fracture reduction, the inverse kinematics solution of PMR is performed.

In the planning procedure, the 6 actuators of PMR will be pre-set to defined initial length. The pre-defined length of these actuators is of arbitrary within a certain range. This procedure is of forward kinematics of Stewart platform. To obtain the fracture alignment and reduction, the position and orientation of moving platform relative to the base platform are known factors, therefore, the solution of the PMR at this situation is of inverse kinematics.

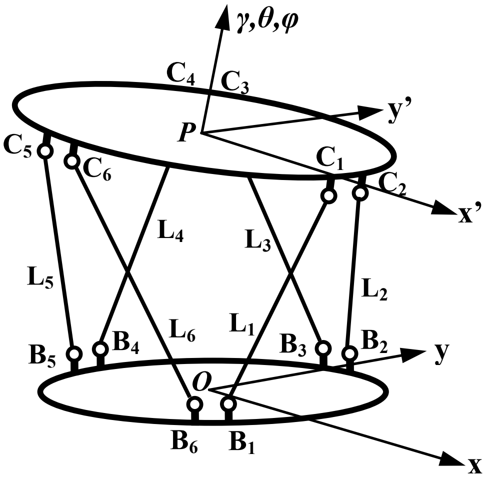

Fig. 3 Illustration of 6-6 SPS Stewart Platform

A brief description of the kinematics solution in both situations is described as following:

a) Forward Kinematics: In the initialization stage, the pre-set lengths of 6 actuators are defined when PMR is assembled and secured on the two fractured femoral segments. Referring to Fig. 3, the **O-xy** plane is representing the base platform while the **P-x'y'** plane is representing the mobile platform. L_i (i =1,2,…6) are representing the lengths of actuators and C_i , B_i (i=1,2,…6) are the locations on both mobile and base platforms connecting two ends of actuators L_i. From this figure, the vectors of actuators can be represented as:

$$\mathbf{L_i} = \mathbf{B_i} - \mathbf{C_i} \quad (i = 1,2,\ldots 6) \qquad (1)$$

And their lengths can be obtained from (1) as

$$L_i = \|\mathbf{L_i}\| = \|\mathbf{B_i} - \mathbf{C_i}\| \quad (i = 1,2,\ldots 6) \; (2)$$

The vector of direction angles ***γ,θ,φ*** and location coordinates ***x,y,z*** for mobile platform, in theory, should be able to be obtained from (2). However, in reality, there is no simple numerical solution because of the cyclical and complexity of trigonometric multivariate functions. Xiong YL et al. [15] presented in the literature "Robotics" their mathematic model based on the assumption that any rigid body in space can be represented by an orthogonal matrix. To illustrate the mobile platform of PMR, such orthogonal matrix **[T]** can be found. The **[T]** is the orientation cosine matrix of mobile platform relative to the base platform [16]. Thus the coordinates **B'ᵢ** of joints connecting to actuators on the mobile platform **P-x'y'** B_i i = 1,2,…,6 and the coordinates $\mathbf{B_i}$ on the base platform **O-xy** satisfies the equation:

$$\begin{Bmatrix} B_{ix} \\ B_{iy} \\ B_{iz} \end{Bmatrix} = [\boldsymbol{T}] \begin{Bmatrix} B'_{ix} \\ B'_{iy} \\ B'_{iz} \end{Bmatrix} + \boldsymbol{P} \quad (3)$$

In the above equation,

$$[\boldsymbol{T}] = [\boldsymbol{u} \quad \boldsymbol{v} \quad \boldsymbol{u}\times\boldsymbol{v}] = \begin{bmatrix} u_1 & v_1 & u_2v_3 - u_3v_2 \\ u_2 & v_2 & u_3v_1 - u_1v_3 \\ u_3 & v_3 & u_1v_2 - u_2v_1 \end{bmatrix}$$

And

$$\boldsymbol{P} = [x \quad y \quad z]^{\boldsymbol{T}}$$

Here ***P*** is the position vector on O-xy coordinate system of base platform. It is the geometric center *P* of mobile platform.

Since **[*T*]** is an orthogonal matrix, it satisfies the following constraints:

$$\sum_{i=1}^{3} u_i^2 = 1; \sum_{i=1}^{3} v_i^2 = 1; \sum_{i=1}^{3} u_i v_i = 0; (4)$$

Combining (3) and (4), there are 9 simultaneous equations with 9 unknowns. i.e.

$$[x, y, z, u_1, u_2, u_3, v_1, v_2, v_3]$$

Given each $R_c, R_b, \omega_b, \omega_c$

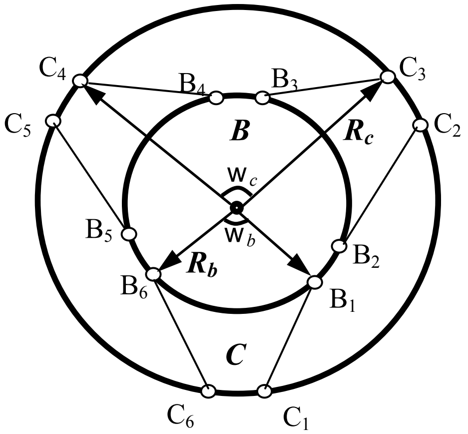

Fig.4 Top View of Stewart Platform

By simple derivations, for each set of given parameters there will be a set of up to 28 solutions.

$$[x, y, z, u_1, u_2, u_3, v_1, v_2, v_3]$$

The above solutions can be further derived as the following:

$$\begin{aligned} \gamma &= arctan2(\sqrt{u_3^2 + v_3^2}, u_1v_2 - u_2v_1) \\ \theta &= arctan2(u_3v_1 - u_1v_3, u_2v_3 - u_3v_2) \\ \varphi &= arctan2(v_3, -u_3) \end{aligned}$$

In summary, for the given set of arbitrary parameters including the lengths of 6 actuators of Stewart Platform,

$$R_c, R_b, \omega_b, \omega_c$$

and L_i (i = 1,2,…6)

There exist up to 28 sets of analytical solutions.

One issue which needs to be addressed is that not all analytical solutions are valid in the real world. For example, a set of numeric solution could be valid mathematically when portion area of mobile platform fells at one side of base platform plane while other portion fells at the other side. In reality, it is not possible for the two rigid bodies passing through each other in 3D space (a 3-D space collision problem).

To eliminate invalid forward kinematics solutions, each set of solutions needs to be tested and validated based on the criterion set according to the structural feasibility. The invalid solutions elimination algorithm has been implemented after the forward kinematics solutions are obtained. At the beginning of the procedure, the coordinates of all 6 actuator joints on mobile platform are solved. Then whether all 6 joints on mobile platform fell on the upper side of the based platform plane is tested. It would be an invalid set of solutions if it does not satisfy the above condition and it will be eliminated. The second validation test for the solution is that one actuator could be crossing to the neighboring actuator because of severe twist between mobile and base platforms. The solution could be good mathematically but there is no such an applicable PMR in the real world.

b) Inverse Kinematics: The procedure for fracture alignment and reduction planning takes position and orientation parameters of mobile platform as known factors and the lengths of 6 actuators as unknowns. Solutions of inverse kinematics of Stewart Platform are presenting the same problem as to take the position and orientation of output module of the robot as known factor and to find the position and orientation of input module. By applying the equation (2), i.e.

$$L_i = \left\| \mathbf{L}_i \right\| = \left\| \mathbf{B}_i - \mathbf{C}_i \right\| \qquad (i = 1,2,\ldots 6) \qquad (2)$$

the lengths of all 6 actuators can be obtained from vectors of connecting joints on the mobile and base platforms [16].

D. Two Step Operations to Achieve Better Reduction

In order to achieve better fracture reduction, a real time fine adjustment for the fracture reduction can be performed after the reduction is considered not accurate enough. The fine adjustment of PMR will perform anterior, posterior, medial and lateral in small amount of movement for distal portion of femoral fragment. This fine adjustment is performed in real time while the C-Arm X-Ray is viewed. The monitoring of the fine adjustment can be conducted in a neighboring room, or even in a remote site with joystick typed parallel manipulator. The fine adjustment of the fracture reduction will minimize the remaining lateral translation and axial discrepancy errors satisfactorily.

III. RESULTS

Eight femoral sawbones' models were artificially broken into eight different fracture patterns. All fracture patterns have characteristics of distal segments overlapping with proximal segments. The positions of the distal segments overlapping with proximal segments were as follows: anterior, posterior, medial, lateral, anterior-medial, anterior-lateral, posterior-medial and posterior-lateral. Therefore, the reductions were all following the initial tractions. The reduction errors of eight artificial fracture patterns were recorded. These errors include axial discrepancy, lateral translation and angular deformity by coarse traction and reduction, axial discrepancy and lateral translation by fine adjustment. The statistic showed that the mean errors were 1.31+-0.45mm for axial discrepancy, 2.43+-0.49mm for lateral translation, 2.26+-0.23mm for angulation in coarse step and 0.63+-0.19mm for axial discrepancy, 0.75+-0.26mm for lateral translation in fine adjustment step, as showed in table I. The table bellow describes the errors recorded in different conditions.

TABLE I
REDUCTION ERRORS IN DEFERENT FRACTURE SITUATIONS

Fx Methods	Traction (mm) and (degree)			Fine Adj (mm)	
	Axl def.	Trans.	Ang.	Axl def.	Trans.
Distal Ant.	1.5	2.5	2.1	0.5	0.5
Distal Post.	1.0	2.5	2.4	0.5	1.0
Distal Med.	1.5	3.0	2.5	0.8	1.0
Distal Lat.	1.0	1.5	1.9	0.5	0.5
Distal Ant-Med	2.0	2.5	2.0	0.5	1.0
Distal Ant-Lat	1.5	2.0	2.3	1.0	0.5
Distal Post-Med	0.5	2.5	2.5	0.5	0.5
Distal Post-Lat	1.5	3.0	2.4	0.8	1.0

IV. DISCUSSION

Femoral Shaft Fracture Reduction with PMR on Traction Table is a new concept and innovative approach applying the PMR with traction table. For the entire course of procedure, the total number of X-Ray taken was four, i.e. the distal and proximal joints of healthy femur, the AP and lateral of fracture site of femur. This significantly reduced the radioactive exposure to both the surgeon and the patient. With respect to the error of accuracy, the result is acceptable for such orthopedic application.

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