A Prototype of Robotic External Fixation System for Surgery of Bone Deformity Correction

Yoon Hyuk Kim*, Sang Min Joo* and Soon-Geul Lee*****

* School of Advanced Technology, Kyung Hee University, Yongin, Korea
(Tel : +82-31-201-2028; E-mail: yoonhkim@khu.ac.kr)
* School of Advanced Technology, Kyung Hee University, Yongin, Korea
(Tel : +82-31-201-2028; E-mail: jooslike@hanmail.net)
** School of Advanced Technology, Kyung Hee University, Yongin, Korea
(Tel : +82-31-201-3648; E-mail: sglee@khu.ac.kr)

Abstract: A robotic external fixation system for the surgery of bone deformity correction was developed to simulate the execution process of mal-unioned femur by the adjustment of the joints of the fixation system. An inverse kinematics analysis algorithm was developed to calculate the necessary rotations and translations at each joint of the robotic system. The computer graphic model was developed for validation of the analysis result and visualization of the surgical process. For given rotational and angular deformity case, the surgical execution process using the robotic system was well matched with the pre-operative planning. The final residual rotational deformities were within 1.0°~1.6° after surgical correction process. The presented robotic system with computer-aided planning can be useful for knowledge-based fracture treatment and bone deformity correction under external fixation.

Keywords: Robotic system, Pre-operative planning, Inverse Kinematics, External fixation

1. INTRODUCTION

The surgery of fracture treatment and bone deformity correction with external fixation method has been primarily used to stabilize bone fragments and recover the mechanical alignment in the chronically deformed long bones [1-3]. External fixation has a distinct advantage in bone surgery since it allows adjustment of the bone segments at the osteotomy site. Furthermore, it allows ongoing monitoring and correction of bone segment alignment to avoid residual deformity in rotation and translation. In addition to stabilization and adjustment, external fixation also provides mechanical stimulation at the fracture site through the elastic properties of the pins and the joints [1-3].

In the traditional procedure of external fixation, three orthogonal radiographic images of a deformed long bone are taken in AP and lateral views. Surgeons then perform a pre-operative planning for given deformity correction using the 2D radiographic images. After inserting the pins and applying the fixator in operation process, the surgeons check the alignment of the bone fragments with fluoroscopic images, and then re-adjust the residual deformity by trail-and-errors.

However, this conventional procedure requires long time with surgical experience until achieving the satisfaction of the alignment. In addition, this method cannot avoid a high dosage of fluoroscopic radiation to both patients and surgeons. Moreover, in a complex 3D deformity case, it would be very difficult to prepare the pre-operative planning since the conventional method cannot provide the joint values of the external fixator to achieve the deformity correction.

The purposes of this study were to develop a prototype of robotic external fixation system for bone deformity correction and validate the robotic system with two deformity correction simulation in the laboratory level using sawbones. First, a computer graphic model of a unilateral external fixator and femur was developed to provide a pre-operative planning of optimal bone deformity correction as well as the graphic validation of the planning results. The inverse kinematics analysis algorithm was developed to determine the necessary fixator joint adjustments under given bone deformities and fixator application configurations. A robotic model with the same configuration as the computer graphic model was developed and tested with sawbones in rotational and varus angular deformity cases.

2. MATERIALS AND METHODS

2.1 A prototype of robotic external fixation system with computer graphic model

The prototype of external fixation system was based on the Dynafix® (EBI medical, USA) external fixation system, which is a clinically available fixator. The robotic system is composed of four pins inserted into the bones, two pin clamps, four revolute joints, a central rotary joint, and two prismatic joints (Fig. 1). Thus, the robotic system has 7 degrees-of-freedom (DOF). For constructing the robotic system, a module type servo motor system (DX-116®, Robotis Inc., Korea), which has both control and link units, was used to construct seven rotational and translational joints. The motor system can operate from 0° to 300° of rotation with 0.35° of the resolution, and maximum holding torque of this motor is 27kg·cm. For having clinically realistic configuration, each revolute joint allows 60° of rotation, and the central rotary joint 120° of rotation in each direction from its neutral position. The prismatic joints allow 33mm of translations (Fig. 1). The robotic system can be controlled by Matlab® (Mathworks Inc., USA) combined with the pre-operative planning program in PC.

The computer graphic model of a transversely fractured tibia at the diaphyseal area was modeled from CT data (Visible Human data, NIH, USA). The graphic model of the robotic system was developed and the graphic models were assembled using commercial CAD software (SolidWorks™, Solidworks Inc., USA). Then, computer simulation of the deformity correction surgery was performed using commercial animation software (3D-Studio Max®, Autodesk Inc., USA) in order to visualize the computed results of joint rotation and translation required to achieve the desired fracture reduction process based on the inverse kinematics analysis. In the computer model, the geometric dimensions and configurations of the fixation model are the same as those of the robotic system.

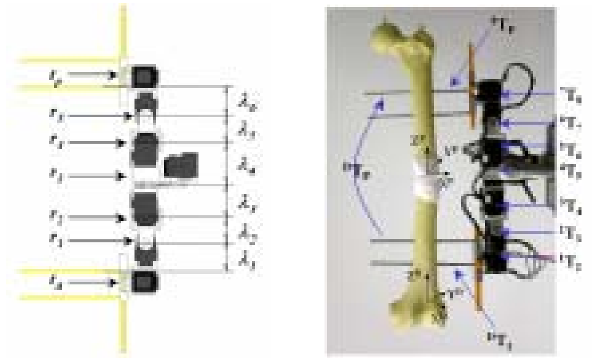
2.2 A pre-operative planning program by the inverse kinematics analysis

The mathematical model of the motion of each link of the robotic external fixation system can be represented as an open-link serial manipulator system interconnected by five revolute and two prismatic joints, thus having 7 degrees-of-freedom (DOF).

A 4 x 4 homogeneous transformation matrix was utilized to express the kinematic loop equations of the robotic external fixation system in order to define six bone deformity parameters at the fracture site [4]. The rotational sequences at the fracture site follows the x-y'-z'' Euler-angle system, and the global coordinate system was fixed to the distal segment of the tibia. All local joint coordinate systems were defined identically to the global coordinate system. In the mathematical model, ${}^{D}\mathbf{T}_{P}$ is the transformation matrix from the proximal femur segment to the distal segment, which was expressed by the matrix or chain equation shown below:

$$ {}^{D}\mathbf{T}_{P} = {}^{D}\mathbf{T}_{1} \cdot {}^{1}\mathbf{T}_{2} \cdot {}^{2}\mathbf{T}_{3} \cdot {}^{3}\mathbf{T}_{4} \cdot {}^{4}\mathbf{T}_{5} \cdot {}^{5}\mathbf{T}_{6} \cdot {}^{6}\mathbf{T}_{7} \cdot {}^{7}\mathbf{T}_{8} \cdot {}^{8}\mathbf{T}_{P} \qquad (1) $$

After substituting the unknown fracture (${}^{D}\mathbf{T}_{P}$) and fixators geometric parameters into the transformation matrices, the seven unknown joint variables, t_d , r_1, r_2, r_3, r_4, r_5 and t_p, can be determined by solving Eq. (1) (Fig. 1). The resulting systems of nonlinear equations were solved using the nonlinear least square optimization method.



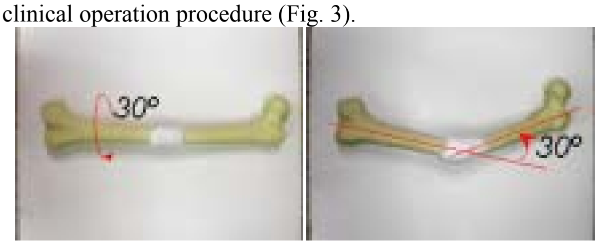
(a) (b)

Fig. 1 (a) Dimensional parameters of the robotic external fixation system: λ_1 = 12.8 mm; λ_2 = 35.0 mm; λ_3 = 44.4 mm; λ_4 = 59.4 mm; λ_5 = 35.0 mm; λ_6 = 15.0 mm. The robotic system is composed of seven joints; "r_1, r_2, r_4, r_5"- the revolute joints; "r_3"- the central rotary joint; "t_p , t_d" - the prismatic joints. (b) ${}^{D}\mathbf{T}_1$ and ${}^{8}\mathbf{T}_P$ represent the rigid body translations of the local coordinate systems between the bone segments and the pin clamps. ${}^{2}\mathbf{T}_3$, ${}^{3}\mathbf{T}_4$, ${}^{5}\mathbf{T}_6$, and ${}^{6}\mathbf{T}_7$ are pure rotations at the revolute joints. ${}^{4}\mathbf{T}_5$ represents axial rotation at the central body. ${}^{1}\mathbf{T}_2$, ${}^{7}\mathbf{T}_8$ represent the translations of the prismatic joints at the pin clamps

2.3 Validation of the robotic system and simulation of the deformity correction surgery

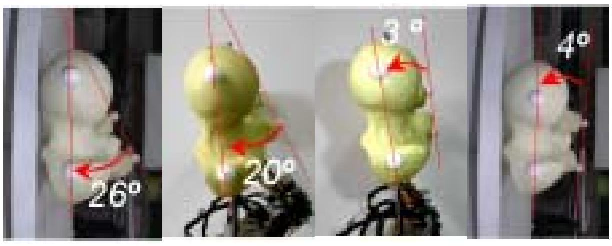
To validate the developed robotic external fixation system, in the first, the accuracy of each revolute was tested. The accuracy of a joint was defined by the difference between the arbitrarily applied joint values in the control program and the resultant values of the joint motor after joint movement.

The simulation of bone deformity surgeries with two mid-shaft malunion cases, a 30° of rotational deformity and a 30° of varus deformity, were tested for the validation of the robotic system (Fig. 2). Using the inverse kinematics analysis results and the corresponding graphic animation, the deformity correction surgery was performed based on the clinical operation procedure (Fig. 3).

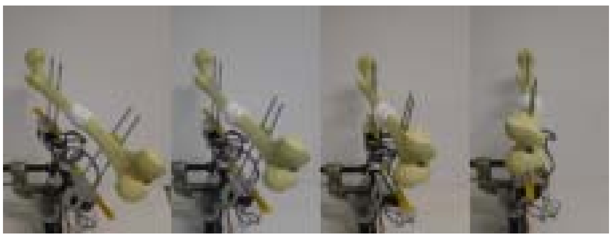


(a) (b)

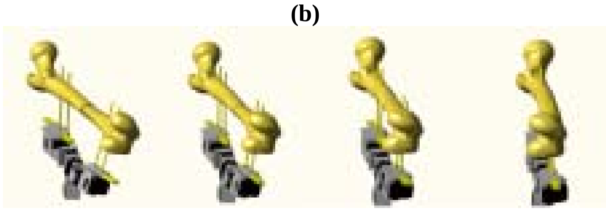
Fig. 2 Saw bone models for the simulation of bone deformity correction surgery. (a) CASE 1 is a mid-shaft malunion with 30° of rotational deformity. (b) CASE 2 is a mid-shaft malunion with 30° of varus angular deformity



1 2 3 4
(a)



1 2 3 4
(b)



1 2 3 4
(c)

Fig. 3 Simulation result of the robotic external fixation system for the correction of 30° of rotational deformity in femur. (a) Axial angle between the distal femoral plateau and the center-line of the proximal femur. The axial angles in Initial deformed femur (1), the deformed femur after cutting (2), after surgical simulation (3), and in normal femur (4) were 26°, 20°, 3°, and 4°, respectively. (b) and (c) represent the surgical simulation of the bone deformity correction in four joint increments using the robotic system and the computer model, respectively.

In the first, the pin holes are drilled and the pins are inserted on the optimal sites. Next, the robotic fixation system was assembled based on the pre-operative planning results and was connected to the pins. Then, the bone cutting was performed following by re-adjustment of residual bone deformity using the joints in the robotic system. Finally, all joint values were changed to the neutral positions with four steps of joint increment.

3. RESULTS

As the accuracy test of revolute joints in the robotic system, the maximum error of the all five revolute joints was below 1.3° for arbitrary input joint values within ±60°. These values coincided with the manufacturer specification.

In the two malunion cases, the solution of the joint variables to correct the given deformities and realign the mechanical axis of the lower extremity was calculated using the inverse kinematics analysis as follows: CASE 1: r_1=-21.7°, r_2=0°, r_3=0°, r_4=0°, r_5=-14.0°, t_p=-28.5mm, t_d=-26.5mm; CASE 2: r_1=-11.4°, r_2=25.7°, r_3=-29.7°, r_4=-25.9°, r_5=-7.5°, t_p =-12.9mm, t_d =-4.7mm (Table 1).

At initial stage, all joint values set to zero at their neutral positions (A on Table 1). To correct the bone deformity before the osteotomy cutting, the necessary revolute and prismatic joint values (B on Table 1) were different those values after osteotomy cutting (C on Table 1). The additional 6° of external rotation in CASE 1 and additional 6° of angulation occurred between distal and proximal fragment after cutting bone. In order to compensation additional rotation, additional measurement of the joint values for the readjustment of the residual bone deformity was needed as C on Table 1.

After correction simulation, the deformity in AP direction between the bone segments in CASE 1 was 1.2° compared with the normal femur, and the deformity in axial view in the CASE 2 was 1.0°. These final deformities were acceptable in clinical situation.

Table 1 Joint values for the correction of deformed femur (r_1, r_2, r_3, r_4, r_5 : °, t_p, t_d : mm)

CASE 1	r_1	r_2	r_3	r_4	r_5	t_p	t_d
A	0.0	0.0	0.0	0.0	0.0	0.0	0.0
B	-16.0	0.0	0.0	0.0	-14.0	-30.3	-28.0
C	-21.7	0.0	0.0	0.0	-15.1	-28.5	-26.5

CASE 2	r_1	r_2	r_3	r_4	r_5	t_p	t_d
A	0.0	0.0	0.0	0.0	0.0	0.0	0.0
B	-9.8	32.4	-35.7	-32.4	-9.8	-13.4	-5.0
C	-11.4	25.7	-29.7	-25.9	-7.5	-12.9	-4.7

(A: Initial joint values, B: Necessary joint values for the correction of deformed femur before cutting bone, C: Joint values for correction of deformed femur after cutting bone)

4. DISCUSSION AND CONCLUSION

External fixation method has been primarily used to stabilize long bone segments following fracture or for bone lengthening [1-3]. This surgical treatment has several advantages such as adjustment capability, elastic fixation, easy removal from the bones, and mechanical stimulation. This surgical method also provides different surgical options such as gradual correction of the residual deformity at the fracture site can be accomplished by rotating and translating the fixator joints gradually on an adjustment plan. Despite the many advantages of external fixation, it has not been favored as the treatment of choice even when clinical indications are favorable for such treatment because of improper pre-operative planning and inaccurate execution from the surgical planning [5]. In order to obtain long-term good clinical results, computer-assisted 3-D pre-operative planning and precise execution of external fixation is necessary [5]. The developed robotic external fixation system could successfully provide the exact execution of the correction surgery of the bone deformity.

In order to have good result of the robotic execution, the planning of surgical process as well as the computer graphic animation is inevitable. In this paper, the inverse kinematics analysis based planning program can provide the necessary joint adjustments of the robotic system for given deformities and these analysis results can be validated through virtual graphic simulation of the surgery.

For the determination of the bone deformity, three orthogonal images were used in this study. This approach provides a cheap and easy-to-use clinical method. However, by incorporating the image-guided system, this bone deformity determination can be precisely performed thus improving the execution result of the robotic system.

Other major issues for improving the simulation result in clinical situation are the consideration of the stability of the fixator joints and the soft-tissue tension.

In the simulation of the bone deformity correction for two mal-unioned femurs, final residual bone deformities were within 1.6° and these results would be within the clinical tolerance. From this result, the robotic system has positive potential in bone fracture treatment and deformity correction surgery.

Finally, the developed robotic external fixation system, combined with the image-guided system and the pre-operative planning program, can be a powerful tool for executing knowledge-based computer-aided fracture treatment, enhancing clinical performance and facilitating changes in the design configuration for the external fixator.

ACKNOWLEDGMENTS

This research was supported by Regional Research Center Program which was conducted by the Ministry of Commerce, Industry and Energy of the Korean Government.

REFERENCES

[1] D. Paley, J. E. Herzenberg, K. Tetsworth et al., “Deformity planning for frontal and sagital plane corrective osteotomies,” *Orthop. Clin. North AM*, Vol. 25, pp. 425-465, 1994.

[2] E. Y. Chao and T. J. Hein, “Mechanical performance of the standard Orthofix® external fixator,” *Orthopedics*, Vol. 11, pp. 1057-1069, 1988.

[3] R. W. W. Hsu, S. Himeno, M. B. Coventry, and E. Y. S. Chao, “Normal axial alignment of the lower extremities and load-bearing distribution at the knee,” *Clin. Orthop. Related Res.*, Vol. 255, pp. 215-227, 1990.

[4] Y. H. Kim, N. Inoue, E. Y. S. Chao, “Kinematic simulation of fracture reduction and bone deformity correction under unilateral external fixation,” *J. Biomech.*, Vol. 35, pp. 1047-1058, 2002.

[5] E. Y. S. Chao and F. H. Sim, “Computer-aided preoperative planning in Knee osteotomy,” *The Iowa Orthop. J.*, Vol. 15, pp. 4-18, 1995.