SIMULATION OF TIBIAL OSTEOTOMY EXECUTION UNDER UNILATERAL EXTERNAL FIXATION

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INTRODUCTION

Careful planning and accurate execution have been identified as the important factors that can determine the successful clinical outcomes in knee osteotomy. Biomechanical analysis of joint alignment and contact pressure distribution have been used to determine osteotomy level and wedge angle for osteotomy surgery. In order to execute osteotomy surgery according to the preoperative planning, precise surgical procedure and subsequent fixator adjustment are required. Current techniques commonly used for osteotomy surgery include placement of multiple K-wires, measurement of intraoperative fluoroscopic images, and adjustment of the osteotomy angle using a protractor or custom templates/jigs. When the three dimensional osteotomy is planned, the conventional methods would require complex measurement and adjustment during surgery and cause longer operative time. Temporarily, fixator can be used for osteotomy surgery for 3-D adjustment of the osteotomy site, which allows to verify the entire limb alignment in different joint angles and positions before final fixation of the osteotomy site. External fixator can also be used to achieve graduate osteotomy correction using callus distraction. We hypothesize that the external fixator can also be used for precise execution of osteotomy surgery with computer simulation technique. The objective of this study was to develop a simulation model to investigate the feasibility of precise osteotomy execution of high tibial osteotomy (HTO) under external fixation as an example.

METHODS

A unilateral external fixator for High Tibial Osteotomy (DFS® Angular Hinge Clamp, EBI) is composed of four pins inserted into the bone segments, a distal telescoping pin clamp, an angular hinge clamp, a central rotary joint, and four sets of revolute joints (Fig. 1A). The osteotomy plane and its orientation were located at 17 mm below the tibial plateau, based on the Coventry closed-wedge osteotomy method. The deformity of the proximal segment (P) with respect to the distal segment (D), expressed by the transformation matrix, $^{D}\mathbf{T}_{P}$, can be determined radiographically using anatomical landmarks. The relative position and the rotation of each link with respect to the previous link is described using the 4×4 homogeneous transformation matrix. Then, $^{D}\mathbf{T}_{P}$ is equivalent to the transformation of each link of the fixator from the proximal bone segment to the distal segment by the matrix or loop equation:

$$^{D}T_{P} = {}^{D}T_{1}\ {}^{1}T_{2}\ {}^{2}T_{3}\ {}^{3}T_{4}\ {}^{4}T_{5}\ {}^{5}T_{6}\ {}^{6}T_{7}\ {}^{7}T_{8}\ {}^{8}T_{9}\ {}^{9}T_{P}. \qquad (1)$$

$^{D}\mathbf{T}_{1}$ and $^{9}\mathbf{T}_{P}$ represent rigid body translations of the bone along the pins. $^{4}\mathbf{T}_{5}$ represents the axial rotation at the central rotary joint, $^{1}\mathbf{T}_{2}$ and $^{7}\mathbf{T}_{8}$ are for the two prismatic joints, and $^{8}\mathbf{T}_{9}$ is rotation of the hinge clamp about the axis of the fixator. $^{2}\mathbf{T}_{3}$, $^{3}\mathbf{T}_{4}$, $^{5}\mathbf{T}_{6}$ and $^{6}\mathbf{T}_{7}$ are pure rotations at the revolute joints. After substituting the pin length and bone length in the transformation matrices, the kinematic chain equations can be reduced to eight nonlinear equations including the seven remaining unknown variables, and the resulting system of over-determined nonlinear equations was solved using the nonlinear least square method (MATLAB™). A test example of a 10° varus deformity was simulated (Fig. 1B). In addition, 4 mm medial translation, 3 mm anterior translation, 5 mm distraction, and 10° external rotation of the tibial plateau segment in reference to the distal tibia were combined with the varus deformity correction in order to fully illustrate the 3-D fixator adjustability and the analysis method can also provide the refined alignment correction steps during treatment.

RESULTS

In the case of a 10° varus deformity, the solution of the fixator joint variables for closed wedge osteotomy site was obtained for the Dynafix DFS® fixator ($\mathbf{r_1} = 2.1^{o}$, $\mathbf{r_2} = 0^{o}$, $\mathbf{r_3} = 0^{o}$, $\mathbf{r_4} = 0^{o}$, $\mathbf{r_5} = -12.1^{o}$, $\mathbf{r_6} = 0^{o}$, $\mathbf{t_d} = 6.2$ mm, $\mathbf{t_p} = -0.2$ mm) (Fig. 1). In the case of a 10° varus deformity with 4 mm medial translation, 3 mm anterior translation, 5 mm superior translation (distraction), and 10° external rotation, of the tibial plateau component in reference to distal osteotomy surface, the different combinations of the fixator joint variables were obtained to reduce the given deformity. According to the analysis results, the graphic simulation showed a perfect reduction of the wedge gap achieved by changing the fixator joint variables as well as monitoring the potential clinical problems during the procedure (Fig. 2).

DISCUSSION

External fixation has a distinct advantage in its ability to directly adjust the bone deformity intraoperatively in one setting or after surgery by adjusting bone segment through gradual distraction at the osteotomy site. Distraction osteotomy can achieve the advantages of open-wedge osteotomy without the use of bone graft as well as allowing continuous monitoring of joint alignment to avoid residual deformity in rotation and translation. To the author's knowledge, however, there has been no study conducted to evaluate the existing fixator's ability to achieve the deformity correction based on specific application configuration and to determine the precise fixator joint adjustments in order to execute the correction plan accurately.

The results of current analysis and simulation showed that knee osteotomy can be achieved by adjusting a combination of the fixator joints at given magnitudes. The present model and the analysis tool can be used to evaluate the adjustment capability of the current fixator design and its performance. These models and analysis tools can provide the guidelines for callus distraction. By incorporating the present analysis with 3-D joint contact pressure analysis, it can be a useful surgical planning software in 3-D computer-aided osteotomy.

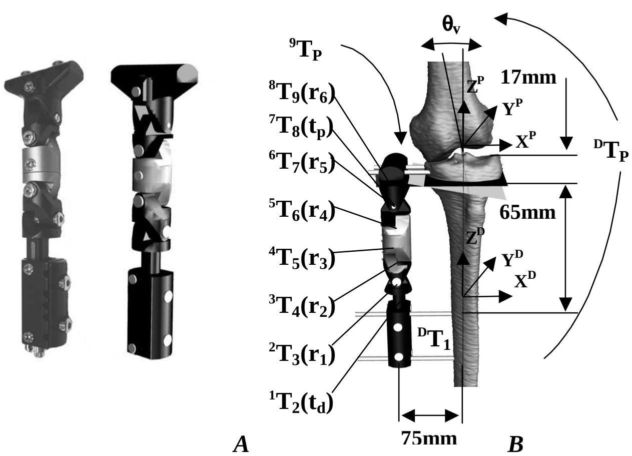

Fig. 1 The HTO tibia-fixator system for 10° varus deformity with the transformation matrices. A. Left, the photo of the fixator and Right, the simulation graphic & biomechanical model of the fixator to facilitate analysis and result visuaization. B. The bone-fixator system before the reduction.

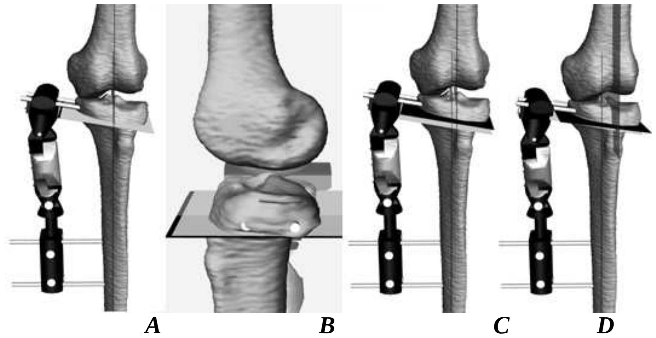

Fig. 2 The configuration of bone-fixator system after correcting the deformity with various rotations and translations; A. 4 mm of medial translation; B. 3 mm of anterior translation in the lateral view; C. 5 mm of distraction; D. 10° of external rotation.

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