INTRODUCTION: In the management of extremity trauma, after inserting the pins and applying the external fixator, adjustment of the bone segment is often necessary to reduce the fracture and correct any residual deformities. For a unilateral external fixator, the ability to adjust rotational and translational deformities is limited. Furthermore, the potential malalignment correction paths to achieve the final bone segment reduction at the fracture site can be infinite depending upon the sequences of fixator joint adjustment selected. If favorable local biomechanical conditions can be reliably and conveniently implemented and maintained using an external fixator, fracture or osteotomy union can be greatly enhanced. This paper presents a model and analysis techniques for a unilateral external fixator to achieve fracture reduction and deformity correction in long bones precisely, through fixator joint adjustment. Combining the kinematic analysis with a graphic model of the tibia and the fixator allowed 3D simulation and visualization of the adjustments required to reduce fracture or correct bone deformity after osteotomy.

METHODS: The Dynafix® (EBI, Parsippany, New Jersey) unilateral external fixator is composed of four pins inserted into the proximal and distal bone segments, two telescoping pin clamps, a central rotary joint, and four sets of revolute joints. A transverse fracture was simulated at the midshaft of the tibia and the bone segments were modeled as rigid bodies. The malalignment of the proximal segment (P) with respect to the distal fragment (D), expressed by the transformation matrix, \( T_{DP} \), was determined radiographically using anatomical landmarks. The relative position and the rotation of the \( i+1 \)th link with respect to the previous \( i \)th link is described using the 4 x 4 homogeneous transformation matrix, \( T_{i+1} \{1, 2 \} \).

In the mathematical model of the Dynafix fixator, \( T_{TP} \) 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:

\[
\begin{align*}
D_{TP} &= D_{T_1} T_{1T_2} T_{2T_3} T_{3T_4} T_{4T_5} T_{5T_6} T_{6T_7} T_{7T_8} T_{8TP}. \\
\end{align*}
\]

\( D_T \) and \( D_P \) represent rigid body translations of the bone along the pins. \( T_2 \) and \( T_3 \) represent rigid body translations in the direction of the telescoping slider mechanism. \( T_7 \), \( T_8 \), \( T_9 \), and \( T_4 \) are pure rotations at the revolute joints, and \( T_5 \) represents a rotation at the central rotary joint. Unknown variables, representing the fixator adjustment required to reduce the deformity in the transformation matrices, can be determined by solving the matrix equation (1) based on known geometric information of the fixators. 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®, Mathworks, Massachusetts). A clinically challenging reduction example of a 30° rotational malalignment about the bone long axis and a 6 mm fracture gap was simulated to validate the model and analysis (Fig. 1).

RESULTS: For a 30° rotational malalignment and a 6 mm fracture gap, correcting the deformity required large rotations at the two inner revolute joint and the rotary joint in the Dynafix model (Fig. 2). The calculated rotations from the distal revolute joint to the proximal revolute joint were \( r_1 = 14.7° \), \( r_2 = -44.1° \), \( r_3 = 41.9° \), \( r_4 = 42.3° \), and \( r_5 = 14.9° \). The translations at the telescoping clamps, \( t_6 \) and \( t_7 \), were both 4.9 mm. Based on the same adjustment solution, different correction sequences generated different reduction paths, some of which produced bone end collisions or excessive soft tissue stretching, excluding them as admissible solutions. A simultaneous adjustment of the all the joints in small increments was simulated as an alternative reduction option. The resulting reduction path was found to be smooth and unique even under different sequential adjustments as long as the fixator joint correction magnitude was small. The graphic model and the step-by-step adjustment animation showed that collision at the bone ends and soft tissue stretching during reduction were completely eliminated (Fig. 3).

DISCUSSION: External fixators are often used in polytrauma cases under the conditions where adequate imaging equipment is not available to fully reduce the fracture. Therefore, subsequent adjustment of the fracture ends may be required. Unfortunately, the relationship between fixator adjustment and bone alignment has not been investigated using established biomechanical analysis techniques. Previous studies have only described bone malalignment and there were no available models that could be used to quantify the fixator parameters for 3D deformity correction. The combination of a rotational and translational deformity is a complicated situation, especially under unilateral external fixation, and thus requires modeling and analytical techniques to work out the correction strategy for adjustment planning purposes. The results of the current analysis show that the deformity can be reduced by adjusting each joint of the fixator.

Since rigid body infinitesimal displacement is sequence-independent, the changes of the joint variables in small increments produced a unique and optimal correction path to eliminate bone fragment collision and excessive soft tissue disturbance regardless of whether the adjustments were provided simultaneously or sequentially. Future versions of the analytical technique should include algorithms to optimize the biomechanical conditions of the fracture or osteotomy site to enhance bone union and remodeling. Aside from the advantages of pre-treatment planning, this model and the analysis are valuable tools to assess the design and application limitations of all fixators of different configurations. In addition, the graphic model can be used to validate the results of the adjustment analysis and allow clinicians to visualize the steps necessary to reduce fractures and correct bone deformity.

SUMMARY: A graphical model and kinematic analysis technique have been developed to study bone fracture deformity correction under external fixation. Among all adjustment options, the optimal bone reduction can be achieved by adjusting all fixator joints in small increments. The model and analysis technique can be used for fixator evaluation and clinical application planning.

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KINEMATIC SIMULATION OF FRACTURE & BONE DEFORMITY CORRECTION UNDER EXTERNAL FIXATION

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Fig. 1 Bone-fixator graphic model with a transverse mid tibial fracture at the mid diaphysis.

Fig. 2 Reduced fracture malalignment and the fixator joint adjustment magnitude.

Fig. 3. The simultaneous adjustment of all joints resulted in a smooth reduction path without bone end collision or soft tissue stretching.