STIFFNESS ANALYSIS OF DYNAFIX EXTERNAL FIXATOR SYSTEM

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INTRODUCTION

It is well known that inter-fragmentary movements at the fracture site and external fixator (EF) stiffness affect the fracture healing pathway [1]. Previous studies have been performed to experimentally quantify the stiffness of external fixators using mechanical testing. Experimental testing has disadvantages, however, because it is time consuming and labor intensive, and such a method is always limited in changing testing configurations and loading conditions. Furthermore, mechanical testing does not allow precise investigation of the fixator components and fracture site behavior that can yield useful information on the fixator component, and local stress to callus at the fracture site. In previous finite element (FE) external fixator models, each fixator joint was modeled as rigid couplings [2]. The objectives of this study were 1) to quantify the stiffness at the fracture site (i.e. system stiffness) under different load conditions using FE analysis techniques, 2) to validate the FE model by comparing the numerical analysis values with the experimental values, and 3) to evaluate the effects of different material, geometrical, and joint stiffness parameters on the system stiffness using parametric analysis.

METHODS

A FE model of the Dynafix^{TM} unilateral external fixator system (EBI, New Jersey) was developed using Abaqus software. Twenty 3-D beam elements were used to model the proximal and distal bone segments, the pins, and the fixator body components (Fig. 1A). The telescopic joints as well as the pin-bone and pin-fixator interfaces were assumed to be rigid. Four revolute joints and a rotary joint were modeled for the fixator body, the inner two rotating about the X-axis, the outer two rotating about the Y-axis, and the central one rotating about the Z-axis, respectively (Fig. 1B). To facilitate direct comparison between our current simulation and previous experimental results, all the geometrical, material, and joint stiffness parameters of the FE model were set according to our previous experimental setting. Table 1 summarizes the nominal values used in the current model. Each revolute joint was modeled as having a finite stiffness value in one rotational degree of freedom (DOF) and assumed to be rigid in the other 5 DOFs.

Four loading conditions, axial compression (AC), anterior-posterior (AP) bending, lateral bending (ML), and axial torsion (TO), were used based on the loading protocol described in a previous experimental study [2]. For AC and TO, the distal bone end was totally constrained to simulate the rigid fixation at the mounting jig. Two different boundary conditions were tested for the proximal end (Fig. 2). For AP and ML bending, two rigid points to support the model were used. For each loading case, the system stiffness was defined as the load divided by the bone displacement or rotation at the fracture site [2].

RESULTS

Table 2 compares the measured and simulated system stiffness values at different loading conditions. Except for the A-P bending, our prediction matches quite well with the experimental results. Under constrained AC (Fig. 2C), the pin diameter is the most critical parameter that could affect the system stiffness followed by the pin offset. The pin elasticity would also affect the system stiffness in a linear fashion although its effect is not as much as the pin diameter and pin offset. However, joint stiffness of the Y revolute joint and fixator diameter have neglectable effect on the system stiffness at the constrained AC (Fig.3A). Conversely, under unconstrained AC (Fig. 2A), the system behavior changes dramatically. The system stiffness reduced to around 500 N/cm, which is six times less than the constrained AC. Moreover, effects of design parameters on the system stiffness also change dramatically. For instance, the joint stiffness of the Y revolute joint becomes a critical factor to determine the system stiffness in the unconstrained AC. The pin diameter curve was found to be getting plateau as the pin diameter increases. This implicated that once the pin diameter exceeded certain value, it could not improve the system stiffness significantly. Anyway, the pin offset is the most important parameter that could affect system stiffness.

DISCUSSION

The stiffness property of the external fixator affects the local biomechanical and biological environment of fracture healing, and this movement can be defined as a 3-D stiffness property of the external fixator system. Using the present analysis model and external loading conditions from gait analyses, the 3-D inter-fragmentary movement of the fracture site can be monitored during daily activities. In order to obtain the optimal conditions of fracture healing, the stiffness property of the external fixator as well as the exact external loading have to be known. The results of this study demonstrated that joint stiffness values affect the system stiffness the fracture site under unconstrained AC. This provides the biomechanical basis for rational guidelines for design improvements and clinical application in external fixators since joint stiffness highly depends upon the applied tightening torque. The Y-revolute joints affected the inter-fragmentary movements for AC and ML, the X-revolute for AP, and the Z-rotary for TO. In addition, the proper selection of boundary conditions in the FE analysis is important to predict the results of stiffness properties of the EF system. The current FE numerical simulation and graphic model can also be used to quantify the local stress field of the fracture callus during compression or distraction procedures, and the reaction force and moment at the fixator joints to predict possible loosening and wear.

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REFERENCES

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(2) Chao EYS, Kasman RA, An KN. Rigidity and stress analyses of external fracture fixation devices – A theoretical approach. J. Biomech., 15:971, 1982.

Table 1. The nominal values used in the current study

Parameters	Nominal values
GEOMETRY	
Pin offset distance (cm)	4.0
Pin separation (cm)	2.6
Pin diameter (cm)	0.55
Bone diameter (cm)	3.8
Fixator diameter (cm)	3.2
MATERIAL	
Pin elastic module (GPa)	200
Bone elastic module (GPa)	28
Fixator elastic module (GPa)	200
Possion ratio for all elements	0.3
FIXATOR JOINT STIFFNESS	
X (Ncm/rad)	64744
Y (Ncm/rad)	64744
Z (Ncm/rad)	44691

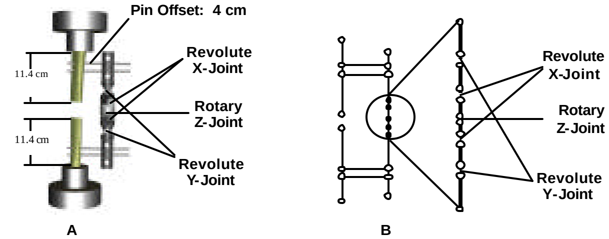

Fig. 1. Fixator-bone system for mechanical testing. A. Experimental configuration. B. Finite element model with 20 beam elements, 4 revolute joints, and 1 rotary joint.

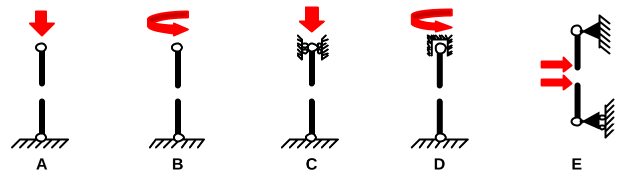

Fig. 2. Boundary conditions used in FE analysis. (A) Unconstrained AC. (B) Unconstrained TO. (C) Constrained AC with 5 restricted DOFs. (D) Constrained TO with 5 restricted DOFs. (E) AP and ML.

Table 2. Comparison of the System stiffness under various loading modes

	System Stiffness Values	
Loading Mode	**FE Model**	**Experiment**
Axial compression (N/cm)	3132	2466
A-P bending (N/cm)	197	502
Lateral bending (N/cm)	3198	2762
Torsion (Ncm/?)	227	155

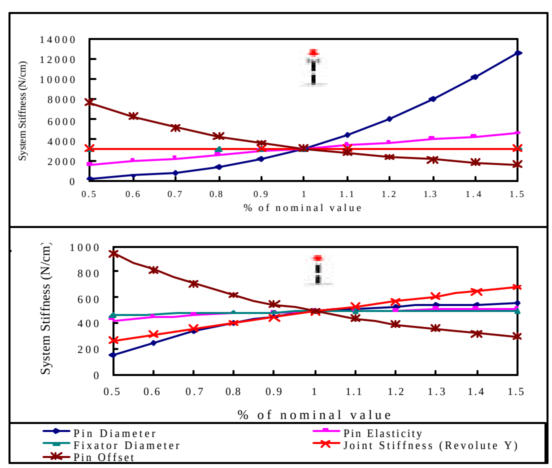

Fig. 3. Effects of different material, geometrical, and joint stiffness parameters on the system stiffness under (A) constrained and (B) unconstrained AC.