EVALUATION OF UNILATERAL FIXATOR WITH SERRATED JOINTS BASED ON BIOMECHANICAL TESTS AND FINITE ELEMENT ANALYSIS

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Abstract: Clinical results suggest that unilateral external fixator lacks versatility in fracture stabilization. To address this limitation, products that incorporate universal joints have been introduced recently. However, there are few studies to date that evaluate biomechanical efficacies of these fixators. In this study, a unilateral external fixator with the universal joints was evaluated systematically with mechanical tests and finite element analysis. Two kinds of mechanical tests - axial compression and cantilever bending - were performed for evaluation of stiffness. Subsequently, stress analysis on the fixator was done with FE models under clinically-relevant loading conditions. Three types of loading conditions - 200N of compression, 2Nm of torsion, and combination of both - were applied to simulate the loading on the fixator. Mechanical test resulted in the stiffness of 35.6N/mm and 9.1Nm/° under axial compression and cantilever bending, respectively. FE analysis indicated high stress concentration at the half-pin and joint parts and these results were similar to those from the mechanical tests. In addition, increase of the von Mises stress near the half-pin was found under the combined load, which may be related to the phenomenon of pin-loosening. Our findings suggested that the weakest point of the unilateral external fixator was the universal joint parts. Therefore, further studies on design factors or materials of the joint parts will be able to add more insights in improving the fracture stabilization capabilities.

Introduction

External fixation is widely used in the treatment of fractures where conservative reduction becomes insufficient because these fractures require extra support to prevent excessive shortening and angulations. It is also popular in limb lengthening and correction of congenital and pathological orthopaedic deformities [1]. The main features that make external fixation attractive include minimal invasiveness, maximum tailorability, and added versatility for maintaining alignment and allowing desired movement simultaneously during fracture healing [2, 3].

There are three kinds of external fixators; unilateral external fixator with half-pin, Ilizarov with tensioned wire, hybrid external fixator with half-pin and tensioned wire [4, 5]. Unilateral external fixator is the most convenient and safe device to operate, but clinical results suggest that unilateral external fixator lacks versatility compared with other external fixators in fracture stabilization [6]. To address this limitation, products that incorporate universal joints have been introduced recently [7]. This new design was intended to improve the correction ability of the external fixator for 3-D bone deformity. However, there is very few studies reporting the effect of the introduced joints on the stiffness of the fixator, which is necessary for a proper evaluation of the mechanical performance in fracture healing of the fixation.

In this study, we investigated the effect of the universal joints on the strength of the unilateral external fixator. A unilateral external fixator with serrated joints was evaluated systematically with mechanical tests based on ASTM standard. Further, finite element analysis was performed to assess stress distribution at the components of the unilateral external fixator.

Materials and Methods

Mechanical test

A unilateral external fixator (n=6, Sinwoo Industrial Co., South Korea) was used for this study. It is composed of ten joints: two translational joints, each with a possible 48mm of extension; two central rotary joints, each with a full 360° of rotation; and six sets of serrated revolute joints, each with a possible ±60° of angulations. (Figure 1).

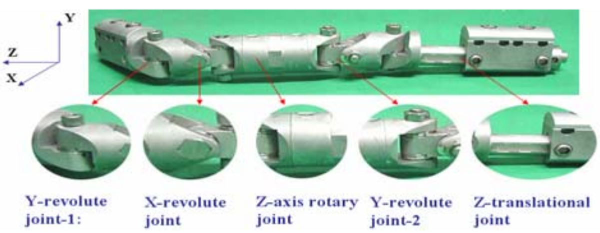

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Figure 1: A unilateral fixator with serrated joints

Simulated tibial plateau fractures were created using the acrylic rod based on ASTM standard [8]. The length and the diameter of the bone models were 200mm and 30mm, respectively. Pilot holes of appropriate size were precisely marked and drilled. External fixators were inserted into the bone models using half-pins and a 20 mm transverse fracture gap was created halfway between the inner most half-pins. Two 6.0 mm diameter half-pins were fixed on each side of the bone model and the bone model-external fixator offset was 50mm (Figure 2). All external fixator were made of alumium alloy and half-pins of Ti6Al4V.

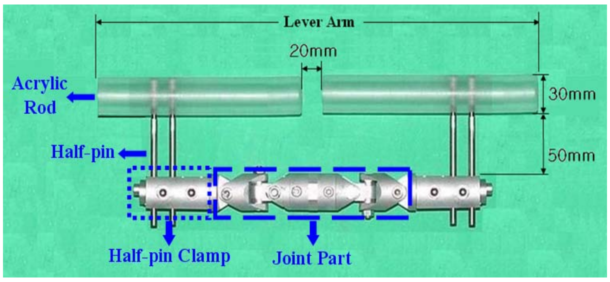


Figure 2: Unilateral fixator with serrated joints and model of fractured bone

Mechanical tests were performed to investigate the effects of the serrated joints to the constructional stiffness of the external fixator. Two kinds of mechanical tests, axial compression and cantilever bending tests, were done (n=3 for each test) according to the guidelines suggested on ASTM F1541-01 [8]. Each of the specimen and the jig were mounted on the mechanical testing machine (MTS858, MTS system Corp., MN, USA) for the tests (Figures 3 and 4). Compressive load was applied at a rate of 10mm/min with the maximum displacement set at 20mm. During each mode of loading, the load-displacement curve was recorded and the slope of the linear portion of the curve was defined as the fixation stiffness.

(a) (b)

Figure 3: Axial compression test of unilateral fixator with serrated joints: (a) Before, (b) After axial compression load

(a) (b)

Figure 4: Cantilever bending test of unilateral fixator with serrated joints: (a) Before, (b) After lateral bending load

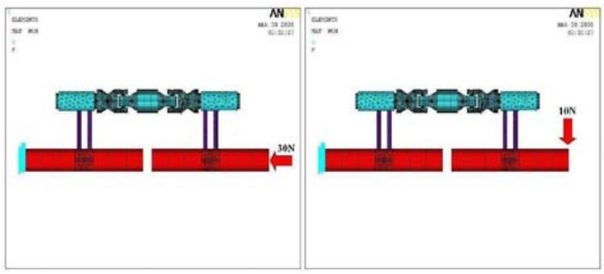
Finite Element Analysis

Finite element model of external fixation system was constructed to analyze the stress distribution due to various loading conditions using commercial software ANSYS (Swan Analysis Corp., USA). Geometry of FE models were made based on their actual CAD drawings. 8-node and 5-node brick elements were used and appropriate material properties were assigned (Table 1).

Under the same loading and boundary conditions as in the mechanical tests, FE models were validated by comparing its results to the stiffness data of the mechanical tests (Figure 5).

Table 1: Material properties of External Fixation System

Components	Young's Modulus(GPa)	Poisson's ratio
Bone model (Acrylic rod)	3	0.37
External Fixator (Aluminium Alloy)	70	0.33
Half-Pin (Ti6Al4V)	113.8	0.33



(a) (b)

Figure 5: Loading & boundary conditions of FE model: (a) Axial compression test, (b) Cantilever bending test

Then, three types of loading conditions – Case I, 200N of axial compression; Case II, 2Nm of torsion; Case III, combination of both – were applied to simulate the loading on the fixator. Axial and torsional loads simulating weight bearing were applied to the proximal and distal ends of the bone model were restricted in all directions of DOF (Figure 6). These load were two

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seventh of the average adult weight bearing (700N) used by Gardner et al. [9] to simulate loading on stable fractures, since reduced weight bearing may be expected in patients with severe injuries and unstable fractures.

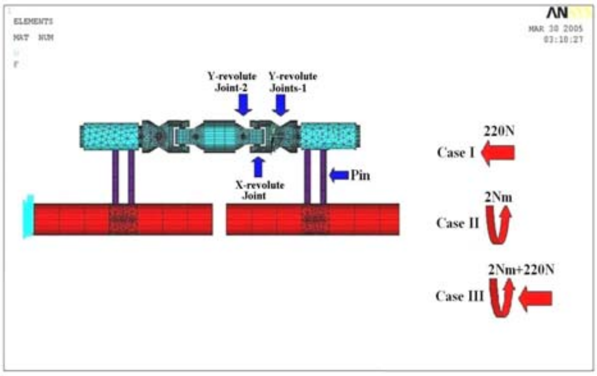


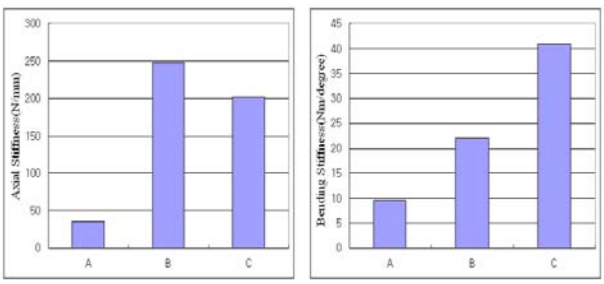
Figure 6: Loading & Boundary conditions of FE model: clinically-relevant loading conditions

Results

Mechanical test

Large deformations in serrated joints were observed in axial compression and cantilever bending condition concurred with the mal-alignment of the external fixation system. Initial relative sliding motion between serrated washers was noted at the Y-revolute joints as well.

Mechanical test resulted in the stiffness of 35.6N/mm and 9.1Nm/° under axial compression and cantilever bending, respectively. These results were then compared to those of commercially available unilateral fixator products such as AO/ASIF standard tubular system (AO, Switzerland) and Single Pin Triax TM (Howmedica, UK) from literature [10]. The specimens in this study had lower axial and bending stiffness compared with the two conventional fixators (Figure 7).



(a) (b)

Figure 7: Test results: (a) Axial compression stiffness, (b) Bending stiffness (A: Specimens of this study with serrated joints, B: AO/ASIF, C: Single Pin Triax TM)

Finite Element Analysis

FE models were validated by comparing its results under the same loading and boundary conditions as in the mechanical tests. Validation results show the FE model is appropriate to analysis stress distribution of the current external fixation system (Figure 8).

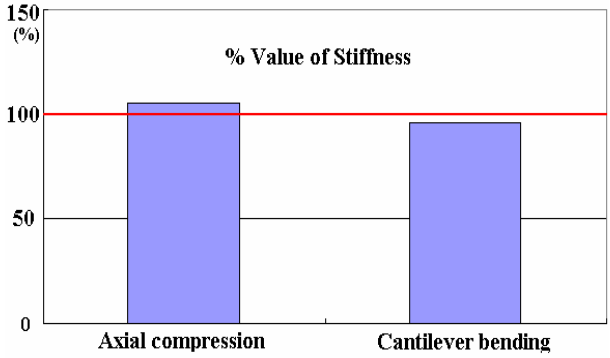


Figure 8: Validities of FE models under Compression & Cantilever bending load

FE analysis indicated high stress concentration at the joint parts and these results were related to large deformations from the mechanical tests. Peak von-Mises stresses at the joints and half pin were tabulated in Table 3. Y-revolute joint 1 showed the highest stress in all loading case. In loading case I, higher stress at the Y-revolute joints than at the X-revolute joint because they rotate along the y-axis under axial load. In loading case II, the lower stresses could be found distally. In addition, increase in the von Mises stress near the half-pin was found under the combined loads, which may be related to the phenomenon of pin-loosening

Table 3: Peak von-Mises stress (MPa) at the components of the FE model

Loading Case	Half Pin	Y-revolute joint 1	X-revolute joint	Y-revolute joint 2
I	118	528	176	458
II	74	89	31	25
III	137	524	185	437

Discussion

Commercially available unilateral external fixator products were introduced for comparison purpose. They are conventional types which have no universal joints. Stiffness test has been performed in the previous study [10]. Despite the comparative small differences in experimental configuration, the external fixation system showed considerable decrease in rigidity or stiffness. This implicated that compromises must be made for the increased revolute joints between the versatility in correctional capability and the decreased rigidity of the external fixation system.

Compared with the Dynafix® Standard Tibia Fixator (EBI, L.P., Parsippany, New Jersey, USA) [7], two more Y-revolute joints and one more central rotary joint were added to the current external fixator design. However, since sliding initiation and large deformation

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were inspected in joint components, such modifications sacrifice the stiffness of the fixator to reach the desirable correction capacity. Additionally, more joints may lead to a longer lever arm in bending test, which may have accounted for fast failure of the external fixation system in bending test. Therefore the large amplitudes of dynamic inter-fragmentary displacement in the axial and angular (longitudinal plane) orientations arising from walking may be great enough to inhibit healing. This may produce mal-union, non-union, and pin–bone interface problems.

During experiment, we found that repetitive manual tightening and loosening of the revolute joint may cause abrasive wear on the serrated washer surface, such components must be inspected and replaced if the device would be re-used. Furthermore, the sharp contrast in stiffness between the Dynafix and current specimen made us to think over our initial experimental setup again. Therefore, further studies on design factors or materials of the joint parts need to be done to add more insights in improving the fracture stabilization capabilities.

Conclusions

Despite the fact the serrated joints provide versatility in surgical management of bone fractures in 3D, it was found that this added revolute joints that were intended for greater versatility in fracture management could inadvertently lead to substantial decrease in stiffness of the whole construct, which may result in unwanted mal-union, non-union, and pin–bone interface problems.

Acknowledgement

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References

[1] PODOLSKY A., CHAO EYS. (2001): ‘Mechanical performance of Ilizarov circular external fixators in comparison with other external fixator.’, *Clin. Orthop.* **293**, pp. 61-70

[2] ZHANG G. (2004): ‘Geometric and material nonlinearity in tensioned wires of an external fixator’, *Clin. Biomech.* 19, pp. 513-518

[3] CHAO EYS., HEIN TJ. (1998): ‘Mechanical performance of the standard Orthofix external fixator’, *Orthop.* **11**, pp. 1057-1069

[4] PALEY D., TETSWORTH K. (1992): ‘Mechanical axis deviation of the lower limbs; preoperative planning of uniapical deformities of the tibia and femur’, *Clin. Orthop.* **280**, pp. 48-64

[5] CAJA VL., KIM W., LARSSON S., CHAO E.Y.S., (1995): ‘Comparison of the mechanical performance of three types of external fixators: linear, circular and hybrid.’, *Clin. Orthop.* **10**, pp. 401-406

[6] PALEY D., CHAUDRAY M., PIRONE AM., LENTZ P., KAUTS D. (1990): ‘Treatment of malunions and mal-nonunion of the femur and tibia by detailed preoperative planning and the Ilizarov techniques’, *Orthop. Clin. Of North America*, **21**, pp. 667-691

[7] KIM YH., INOUE N., CHAO EYS. (2002): ‘Kinematic simulation of fracture reduction and bone deformity correction under unilateral external fixation’, *J. of Biomech.* **35**, pp. 1047-1058

[8] ASTM F1541-01, (2001): ‘Standard specification and test methods for external skeletal fixation Devices’, *Annual Book of ASTM Standard, NY*

[9] GARDNER TN., EVANS M., KENWRIGHT J. (1996): ‘The influence of external fixators on fracture motion during simulated walking’, *Med. Eng. Phys.*, **18**, pp. 305-313

[10] GARDNER TN., SIMPSON H., KENWRIGHT J. (2001): ‘Rapid application fracture fixators – an evaluation of mechanical performance’, *Clin. Biomech.* **16**, pp. 151-159

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