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Stiffness Characteristics of Joshi's External Stabilization System under Axial Compression: a Finite Element Method Based Study

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ABSTRACT
A finite element model of fractured tibia with Joshi's External Stabilizing System (JESS) mounted on it was developed using 3D beam elements in the ANSYS software. The model was loaded in axial compression and the average axial stiffness of the model was calculated. The analytical value of axial stiffness was compared with reported experimental value to validate the finite element model. The validated model was used to carry out parametric studies on the model to determine the axial properties of JESS. It was observed that axial stiffness of JESS increased by 58% when k-wire diameter was varied from 2 mm to 4 mm while keeping other geometric configurations of the device constant; however, the axial stiffness of the device does not show any significant improvement when the diameter of medio-lateral pins in diaphyseal hold were increased. The findings should help in understanding the axial properties of JESS so that it can be used judiciously in clinical applications.
***Keywords* –** JESS, external fixators, tibial fracture, axial stiffness, k-wires, finite element analysis

I. INTRODUCTION

External fixation is a method of stabilization of bone fractures in which a number of percutenous metal pins pass through the fractured bone segments with their ends connected to a rigid frame. Joshi External Stabilizing System (JESS) is an external bone stabilizing device used in the Indian subcontinent. It was designed and fabricated by Dr BB Joshi in late seventies primarily for the treatment of hand trauma [1]. However, due to its low cost and highly versatile nature it evolved with time to be used in the treatment of variety of musculoskeletal disorders. At present, JESS is prominently used in intra-articular distal radial fractures [2], management of idiopathic clubfoot [3], hand trauma and its sequels [4]. Recent applications have been reported about JESS being used in treatment of injuries of tibial plateau and tibial plafond [5].

Many experimental procedures have been employed to study the behaviour of external fixation devices. Yilmaz *et al.* [6] conducted an experimental study to determine the stiffness characteristics of standard and hybrid Ilizarov circular fixators. Stein *et al.* [7] performed a biomechanical study on hybrid ring tubular external fixator to measure and compare the mechanical properties of different hybrid fixators. Schrøder *et al.* [8] performed experimental investigations of four different configurations of the Hoffmann external fixation system to assess its mechanical properties.

Experimental procedures are important in establishing basic characteristics of fixation devices. However, they have some inherent shortcomings. Such procedures are time consuming, costly and need a large number of experimental data. Also, a minor change in the device requires another set of experiments to collect new data. As a result analytical methods such as finite element method have gained popularity for evaluating the mechanical properties of fixation devices analytically. Many researchers have used finite element analysis to study the mechanical properties of external fixation devices. Rybicki [9] presented the role and approach of finite element analysis in orthopedic studies and the application of FEM in the analysis of stresses in intact bones, analysis of fixation devices and prosthetic devices with a review of works carried out by researchers in these areas. Chao and An [10] classified the commonly used external fixation devices according to their geometrical configurations. They proposed a two dimensional and three dimensional beam elements to develop the finite element model of external fixators. Koo *et al.* [11] developed a finite element model using three dimensional beam elements in ABAQUS software and analyzed it for various loading conditions. It was found that under constrained axial compression, the pin diameter is the most critical parameter that could affect the system stiffness followed by pin offset. It was also reported that once the pin diameter exceeded certain value, it could not improve the system stiffness significantly.

Bartel *et al.* [12, 13] developed a model using symmetric and unsymmetrical beam theory and demonstrated that beam theory, if used within its limitations, could provide an excellent model for understanding the overall behaviour of bone-implant systems. Prendergast *et al*. [14] conducted finite element analysis and mechanical testing of unilateral and bilateral external fixators. Watson *et al.* [15] developed a modular FE model of the components of Illizarov external fixation system to predict mechanical properties of any configuration of the device. The first reported study on characterization of JESS was carried out by Kumar *et al.* [16] who conducted an experimental and finite element based investigation to determine and compare the axial stiffness of JESS and proposed a validated FE model of JESS under axial compression.

Present study aims to analyze of the effect of variation in k-wire diameter on overall axial stiffness of JESS while keeping all other geometrical parameters of the fixator constant using finite element method. It will also study the change in axial stiffness of device when the size of medio-lateral pins in diaphyseal hold is varied.

II. MATERIALS AND METHODS

2.1 Geometrical features of JESS

A JESS frame used for treatment of proximal tibial fractures can be configured in two parts, a proximal hold or helmet and a diaphyseal hold. The proximal hold consists of two circular rods of 4 mm diameter curved into a three quarter circular rings mounted on the proximal tibia with help of three percutenous pins (k-wires) inserted at about 22.5º with each other. The second three quarter circular ring has a lesser diameter than the first ring and it is added to reinforce the strength of proximal hold. For a JESS used in treatment of metaphyseal tibial fracture, the k-wire diameters may vary from 2.0 mm to 4.0 mm depending upon the clinical requirements. Universal link joints are used to join k-wires to the outer and inner circular rings with proximal tibia.

The diaphyseal hold is composed of three parallel pins inserted in the tibia diaphysis in medio-lateral plane (m-l pins) below the fracture fragment and are attached to two Z shaped connecting rods on the either side of tibia using universal link joints. The proximal hold and diaphyseal hold are in turn connected to each other with help of two anterior and two posterior connecting rods joining diaphysis hold to the outer ring of the proximal hold. In addition, one half pin is inserted from anterior in anterior-posterior plane to provide further fragment stability. Fig.1 shows the laboratory specimen of JESS configured on steel tubes simulated as tibial bone which was used for developing a three dimensional finite element model in our study.

2.2 Finite element analysis of JESS

The aim of this study was to evaluate the effect of geometric variations on the overall axial stiffness of JESS using a validated three dimensional finite element model of JESS as proposed by Kumar *et. al.* [16]. Therefore, the finite element model of JESS was developed using the identical geometric specifications and material properties as prescribed in the study.

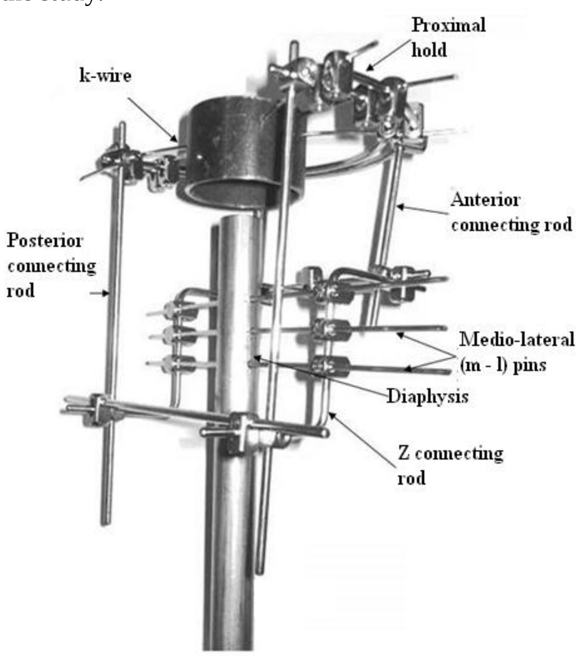

Fig.1 JESS configured on steel tubes

To create the FE model, the structural geometry of the JESS configured on steel tubes was created using ANSYS finite element software. A 15 mm gap was provided between the ends of the hollow steel tubes to represent the metaphyseal tibial fracture. The gap was maintained at 15 mm to ensure the complete load transfer through fixator rather than through the steel tubes. The wireframe model was discretized using 3D beam element (Beam 188). As the different components of the model had different sizes, appropriate section properties were allocated to each component. The discretized model of JESS consisted of 146 nodes and 164 elements. The elastic modulus and Poisson's ratio for the parts of JESS, k-wires, m-l pins & idealized tibial bone segments were taken as 200 GPa & 0.28 respectively.

The idealized pin-bone and pin fixator interfaces and various universal link joints of the JESS were modeled as rigid joints. To measure the axial compression of JESS, the distal end of the model was fixed by setting all degrees of freedom to zero. A vertical compression load was applied to the proximal end. Fig.2 shows the FE model of JESS with applied load and boundary conditions. The model was analyzed for static, linear analysis under axial compression.

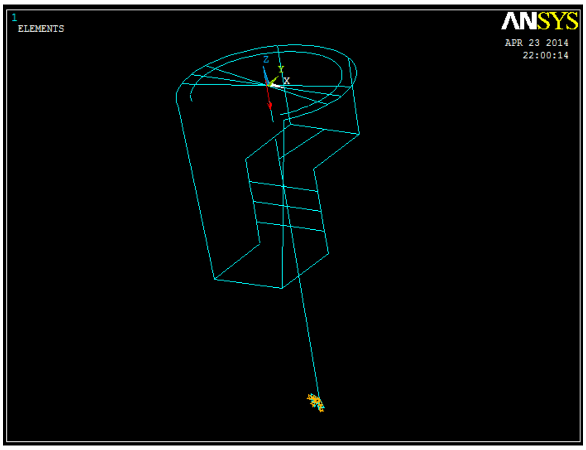

Fig.2 FE model with load and boundary conditions applied

The axial stiffness and corresponding inter fragmentary displacements of the JESS frame during the axial loading were calculated from the FE model. Fig.3 shows the deformed FE model of JESS configured on steel tubes under axial compressive load.

The validated FE model was used to carry out two parametric studies to assess the effect of geometric variations on the axial properties of JESS.

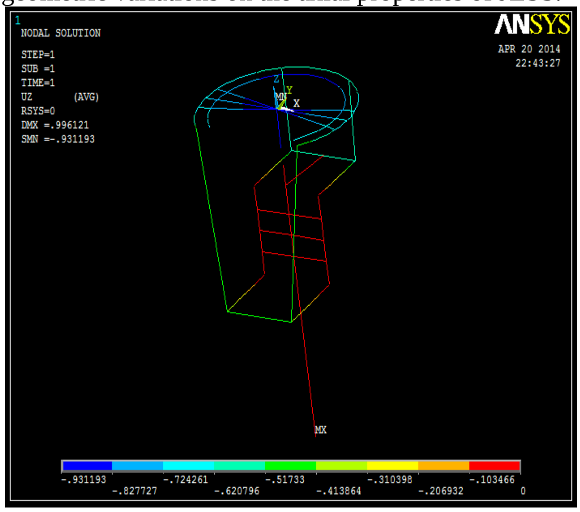

Fig.3 Deformed model of JESS under axial compression

In the first study, the diameter of the k-wires in proximal hold was varied from 2 mm to 4 mm in the step of 0.5 mm and the axial stiffness of the JESS frame was evaluated. All other geometrical parameters were kept identical including the m-l pin diameter. These steps were repeated for another value of m-l pins diameter and variation in axial stiffness was evaluated. This way total four set of data were collected for four different diameters of m-l pins. In the second study, for a selected diameter of k-wire, the diameters of m-l pins in the diaphysis hold were increased from 2.5 mm to 4 mm in a step of 0.5 mm and axial stiffness in each case was calculated. Then k-wire diameter was set to another value and m-l pins diameters were varied to evaluate another set of stiffness data for JESS.

III. RESULTS

The axial stiffness of JESS was calculated by finite element model under individual loading condition. The average axial stiffness obtained by FE analysis having k-wire size of 2 mm was compared with the reported experimental value [16] and was found to be comparable. Thus, the FE model can be used as valid model to simulate the axial mechanical properties of JESS. Effect of geometric variations were studied and it was observed that the average axial stiffness of JESS improved by about 58% on varying the diameter of the k-wires from 2 mm to 4 mm in proximal hold with m-l pin diameter kept at 4 mm and keeping all other geometrical parameters constant. Further, by changing the medio-lateral pins diameter in diaphyseal hold from 2.5 mm to 4 mm the average axial stiffness was increased by only about 6.2% while k-wire diameter was kept constant at 4 mm.

IV. DISCUSSION

Goodship and Kenwright [18] has reported that the mechanical properties of an external fixation device influence the biological environment at the bone fracture and controlled micro-movement of fracture could facilitate secondary healing in the fractured bone. Mechanical properties of fixation devices also affect the outcome of any fixation process. A very rigid fixator can delay healing; on the other hand an over flexible fixation device may lead to increase chances of pin-bone tract infection, mal-union and even non-union in some cases. Therefore, it is extremely important for a surgeon to have a good knowledge of comparative mechanical properties of the fixation device to use it in clinical applications.

The axial stiffness of the JESS was calculated by developing a three dimensional finite element model using 3D beam elements in ANSYS software. It was observed that the average axial stiffness of the JESS increases nonlinearly with increase in the diameter of k-wires and the overall increase in axial stiffness by changing the diameter of k-wires from 2 mm to 4 mm was about 58%. The change in axial stiffness for each size of k-wire with m-l pins diameter maintained at 2.5 mm is shown in figure 4.

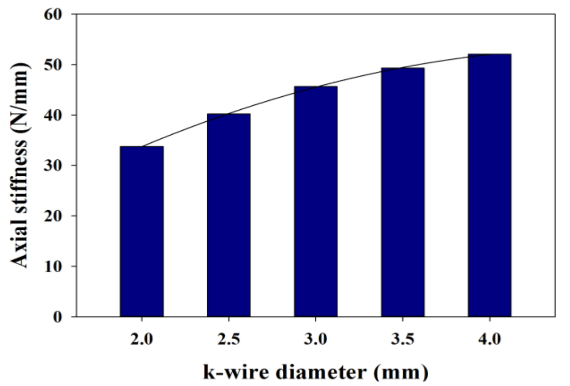

Fig.4 Variation in axial stiffness of JESS with change in k-wire diameter (m-l pins diameter 2.5 mm)

It was also observed that incremental gain in axial stiffness from diameter 2 mm to 4 mm drops as the k-wire diameter increases. The gain in axial stiffness was about 19% when the diameter of k-wire was changed from 2 mm to 2.5 mm however, the increase was only 5.5% when the diameter was changed from 3.5 mm to 4 mm. As 4 mm k-wire size is the maximum pin diameter used in a standard JESS under clinical application therefore, axial stiffness was not calculated for higher values of k-wire size beyond 4 mm. The overall improvement in axial stiffness was about 54% on variation of k-wire size when m-l pin diameter was fixed at 2.5 mm and it was about 58% when m-l pin diameter was fixed at 4 mm. Fig.5 shows the effect of variation in k-wire diameters on axial stiffness of JESS.

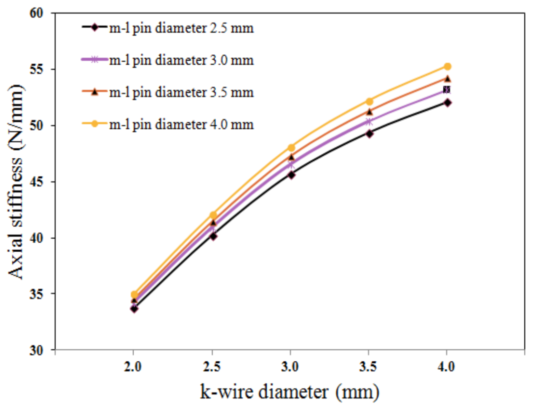

Fig.5 Variation in axial stiffness of JESS for different set of m-l pin sizes

In the second part, k-wire diameters were fixed and m-l pins diameter in diaphysis hold was varied from 2.5 mm to 4 mm in the step of 0.5 mm and for each case, axial stiffness of the device was calculated. These five sets of observations are plotted fig.6. It can be seen that by changing the m-l pins diameter from 2.5 mm to 4 mm while keeping the k-wire diameter constant increases the axial stiffness by a mere 3.5% to 6.2%. It can therefore be suggested that the size of medio-lateral pin does not play a significant role in determining the axial stiffness of the fixator. On the other hand, the k-wire size used in proximal hold plays a major role in controlling the overall axial stiffness of the JESS fixation device and can be manipulated to improve the stiffness of JESS in clinical applications.

V. CONCLUSION

Finite element model of JESS configured on steel tubes was developed with 3D beam element in ANSYS software and two parametric studies were conducted. Results show that the axial stiffness of the JESS can be improved by changing the diameter of k-wires in proximal hold. Thus, k-wire sizes play a significant role in determining the axial properties of JESS.

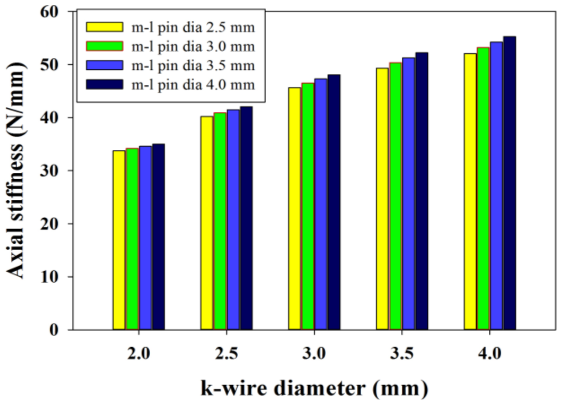

Fig.6 Variation in axial stiffness for varying medio-lateral pin diameter

The results of the study are based on a standard configuration of JESS device commonly used in stabilization of tibial fractures. However, the JESS is available in slightly different modules by different manufacturers in India. The exact configurations of JESS may vary in clinics depending upon surgeon's own judgment and practice. Therefore, the above results may not be generalized for all types of the JESS configurations. Nevertheless, the present study suggests a way by which axial stiffness of JESS frame can be improved as per the clinical requirements.

Conflict of interest statement

All authors hereby declare that this study was not funded by any agency and there are no personal relationships with anyone who could influence the results of present study.

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