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STRUCTURAL ANALYSIS AND EXPERIMENTAL TESTING OF EXTERNAL FIXATOR SYSTEM UNDER AXIAL COMPRESSION

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ABSTRACT
This work presents a segment of research results of mechanical stability of the Sarafix external fixation system, applied to a tibia, in the case of an unstable fracture. The research has been conducted using structural analysis of one of the Sarafix fixator configurations by application of the finite element method (FEM) and experimental testing. 3D geometrical and FEM model of fixator configuration have been formed, whence a structural analysis has been performed using CATIA V5 software system. Structural analysis and experimental testing of Sarafix fixator have been performed under axial compression. Values of bone segments displacements at the point of load and fracture gap have been analyzed based on which values of axial construct stiffness and fracture gap stiffness have been determined. Verification of the results obtained from a structural analysis through experimental testing has been carried out by comparing values of an appropriate component of displacement at the point of load.
Keywords: external fixator system, structural analysis, experimental testing, axial construct stiffness, fracture gap stiffness.

1. INTRODUCTION
External fixator systems are medical devices for stabilization of bone fractures, and their compliance aims at producing an interfragmentary motion that promotes rapid and successful healing. The aim of the fixation technique is anatomical reduction and immobilization of the bone segments, as well as maintenance of this anatomical stabilization concept throughout the treatment by external stiffening of the fracture gap separating the bone segments. This aim is achieved by an external frame that is connected percutaneously to the bone segments by pins or wires. Directions and intensity of interfragmentary motions have the crucial importance on rapid bone healing [3]. It is possible to control interfragmentary 3D displacement of the fracture gap using FEM model. Optimal mechanical environment, which promotes bone healing, has not been completely defined yet. Both excessively high and excessively low interfragmentary motions were shown to have adverse effects on bone fracture healing. Moreover, interfragmentary displacements parallel to the fracture surfaces were shown to result in pseudo-arthrosis instead of fracture healing.
This work presents results of structural and experimental analysis of one of the most used configuration of *Sarafix* external fixator system in the case of an unstable tibial fracture (configuration C, type 4+4). Fixator *Sarafix* presents unilateral biplanar external fixator of high flexibility, enabling its application on complete human skeleton. Unstable fractures at the middle of tibia have been analyzed with fracture gap of 20 and 50 mm (severe extensive injuries with a considerable defect of bone structure).

Sarafix fixator was attached to proximal and distal tibia bone segment modeled with cylindrical wooden models known physical properties. Bone models were supported on ball joints, while maximal axial loading force applied to the proximal bone model was: $F_p = 600$ N [1].

2. STRUCTURAL ANALYSIS

3D geometrical modelling of components and assemblies of the *Sarafix* fixator have been performed using CATIA V5 modules *Part* and *Assembly Design*. Afterwards, FEM modeling and linear structural analysis have been performed [2].

Material of wooden bone models (beech) was defined orthotropic, as materials of the fixator construction (stainless steels) were modeled isotropic. Solid elements, types of linear and parabolic tetrahedral, were used for modeling structure of components *Sarafix* fixator. Join elements, type spider, were used for modeling joints between components and virtual part [1].

Most biomechanical studies of the external fixation analyze only total characteristics of stiffness of diverse types of fixators and configurations. Fixator construct stiffness is an important characteristic, but it cannot provide direct information about displacement of a fracture gap. Precise information can be provided analyzing relative displacements of end bone segments under simulated conditions of loads. Values of proximal bone segment displacements at the point of load have been analyzed based on which values of axial construct stiffness have been determined. Moreover, values of proximal and distal bone segment displacements at the fracture gap have been analyzed, based on which values of fracture gap stiffness have been determined (Figure 1.) [1].

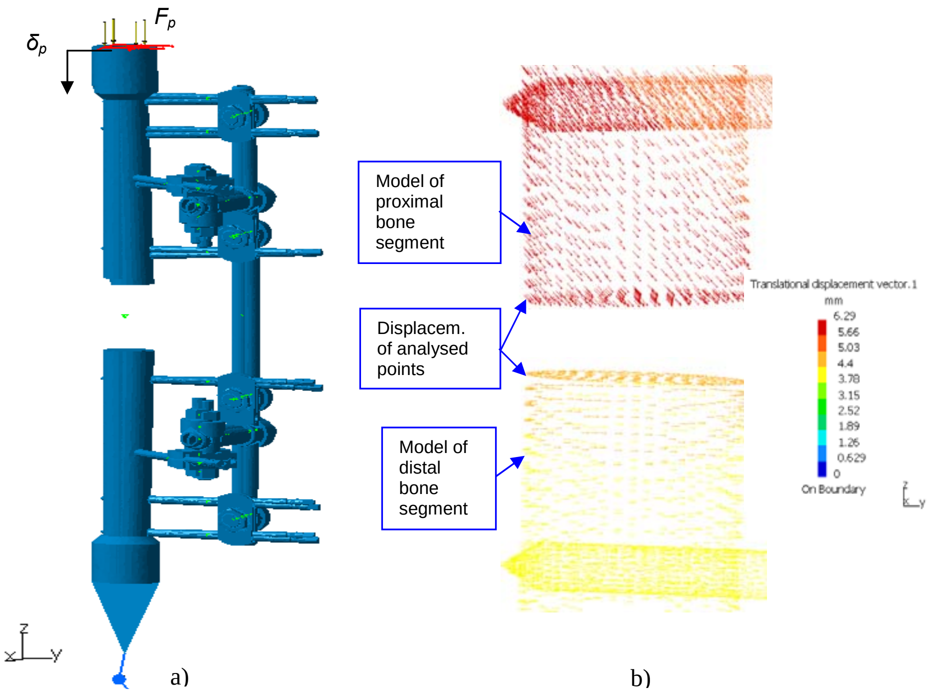

Figure 1. Deformed and non deformed structure of the system (a) and translation displacement vectors of points at the fracture gap (b) under maximum axial load

Axial construct stiffness of the fixator (C_p) was calculated using following equation:

$$C_p = \frac{F_p}{\delta_p} \qquad \text{... (1)}$$

where:

F_p – is the applied axial loading force (N),
δ_p – is the axial displacement of proximal segment at the point of load (mm).

Absolute displacements of analyzing points at the proximal and distal fracture endplate in the x, y and z direction were determined. Analyzing points were selected in such a manner as to resulting vector of relative displacements (R) have maximal value (Figure 1.).

Relative craniocaudal and lateromedial displacements (x and y direction) and axial displacements (z direction) for analyzed points were calculated as [3]:

$$r_{D(x)} = D_{p(x)} - D_{d(x)}$$
$$r_{D(y)} = D_{p(y)} - D_{d(y)} \quad \text{... (2)}$$
$$r_{D(z)} = D_{p(z)} - D_{d(z)}$$

where:

$r_{(D)x}$, $r_{(D)y}$ and $r_{(D)z}$ – is the relative displacements at the fracture gap in the x, y and z directions (mm),

$D_{p(x)}$, $D_{p(y)}$ and $D_{p(z)}$ – is the absolute displacements of points at the proximal fracture endplate in the x, y and z direction (mm),

$D_{d(x)}$, $D_{d(y)}$ and $D_{d(z)}$ – is the absolute displacements of points at the distal fracture endplate in the x, y and z direction (mm),

The gap stiffness was calculated as the applied force divided by total displacement at the analyzing points [3]:

$$C_{pp} = \frac{F_p}{R} = \frac{F_p}{\sqrt{(r_{D(x)})^2 + (r_{D(y)})^2 + (r_{D(z)})^2}} \quad \text{... (3)}$$

Values of displacement of proximal and distal model of the bone segment under maximal axial load are presented in Table 1. In addition, axial construct stiffness and gap stiffness values for analyzed configurations are given in same table. Results presented for configuration C50 were obtained using structural analysis and experimental testing, while results presented for C20 configuration were obtained using experimental testing.

Table 1. Values of stiffness and displacements under maximum axial load

Configuration	*Displacement of the proximal segment,* mm						*Displacement of the distal. segment,* mm			*Max. relat. displ. at the gap,* mm	*Axial displ. at the point of load,* mm	*Gap stiff.,* N/mm	*Axial const. stiffn.,* N/mm
	Point of load			Fracture gap			Fracture gap						
	x	y	z	$D_{p(x)}$	$D_{p(y)}$	$D_{p(z)}$	$D_{d(x)}$	$D_{d(y)}$	$D_{d(z)}$	R	δ_p	C_{pp}	C_p
C50 FEM	0	0	-4,18	0,53	4,14	-4,36	0,53	4,29	0,22	4,58	4,18	130,93	143,54
C50 Exp.	0	0	-4,35	-	-	-	-	-	-	-	4,35	-	137,93
C20	0	0	-3,43	-	-	-	-	-	-	-	3,43	-	174,93

3. EXPERIMENTAL TESTING

Experimental testing of *Sarafix* fixator configuration under axial compression was performed on the Zwick material testing machine (Zwick GmbH & Co., Ulm, Germany, model 143501) using supports for holding of models. After mounting of analyzed configurations of *Sarafix* fixator on wooden bone models, they were positioned in the material testing machine (Figure 2.).

With this method, load was transmitted from bone models onto the fixator. The ends of the proximal and distal bone models were fixed in the testing machine with a ball joint to the load cell and the basement, respectively (Figure 2.) [1].

In the axial compression, the configurations were loaded up to 600 N axial load, under load control at the rate of 2 N/s. In addition, unloading of the fixator constructions was performed at the same rate.

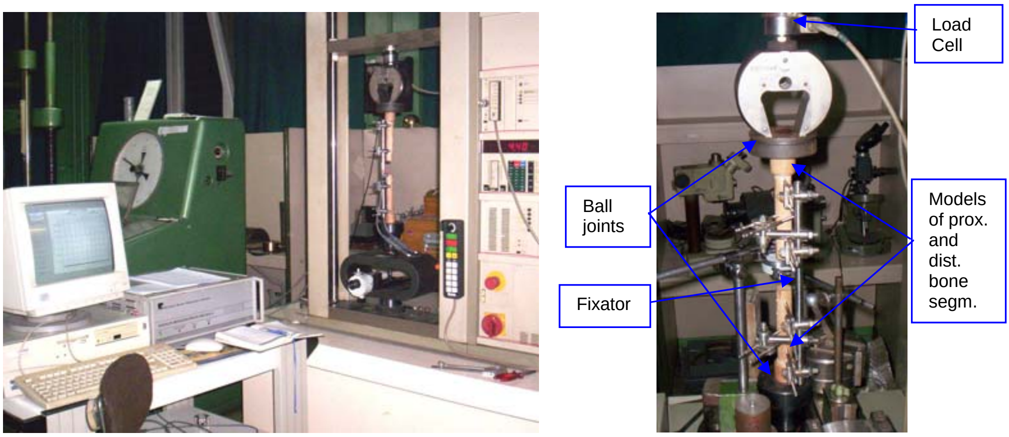

Figure 2. The experimental setups for axial compression tests

Diagrams of the axial displacement proximal model of the bone segment at the point of load for configurations C20 and C50 of *Sarafix* fixator are shown in Figure 3.a. The loading phase is denoted by continuous lines and the unloading phase by discontinuous lines.

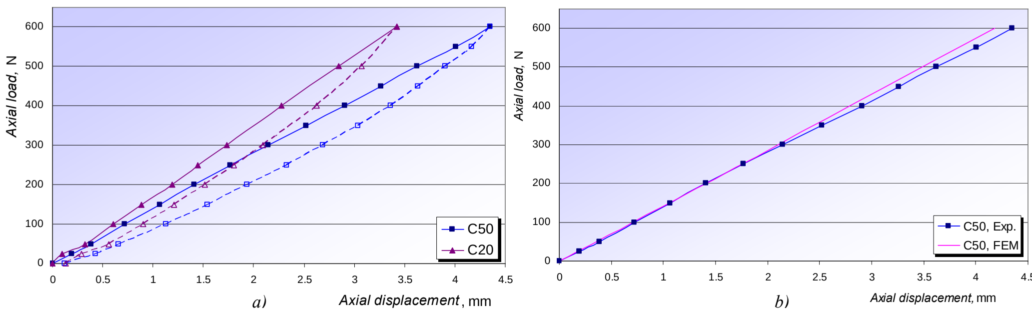

Figure 3. Diagrams of the axial displacement (a) and comparative diagram of the axial displacement (b) (experimental and FEM analysis) at the point of load

Diagrams of the axial displacement at the point of load for the configuration C50, obtained from the structural analysis using the FEM and experimental testing, are shown in Figure 3.b.

4. CONCLUSIONS

Hysteresis loops of compression are noticed on the diagrams of the axial displacement. The spontaneous capability of relaxation of the C *Sarafix* fixator configuration in the measuring range was 97,6%. The axial construction stiffness of the C20 *Sarafix* fixator configuration is greater than C50. Results of the axial displacement obtained from a structural analysis are deviate with regard to the results of the experimental testing 3,9%, which verified the results obtained by the structural analysis, i.e. the formed FEM model of the was verified.

5. REFERENCES

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