

Analysis of Mechanical Stability for External Fixation Device in the Case of Anterior-Posterior Bending

Nedim Pervan^{1*}, Adis J. Muminović¹, Elmedin Mešić¹, Muamer Delić¹, Enis Muratović¹

¹ Faculty of Mechanical Engineering, University of Sarajevo, Vilsonovo šetalište 9, Sarajevo, Bosnia and Herzegovina

* Corresponding author's e-mail: pervan@mef.unsa.ba

ABSTRACT

Analysis of mechanical stability for external fixation device Orthofix in the case of anterior-posterior bending is carried out in this paper. Device is applied to the lower leg for the case of unstable fracture. Real device is measured and 3D CAD model is developed. CAD model is used for numerical structural stress analysis which is carried out using CATIA V5 software. Results for displacements are obtained for selected critical places on the device and for the place of fracture. In addition, values of principal and von Mises stresses are obtained and analyzed. Using obtained results, conclusions about mechanical stability of device are formulated.

Keywords: external fixation device, stiffness analysis, interfragmentary displacements, principal stresses.

INTRODUCTION

Basic goal of fracture fixation is to enable fractured bone to be used as soon as possible. Mechanical and biomechanical characteristics of fixation devices have a big influence on the speed and quality of healing process [1]. During healing process all forces generated during bone movement are transferred to the fixation device. Behavior of device is defined by its mechanical and biomechanical properties [2].

From the first fixation device up to today their types, methodology of selection, places of usage and types of application has changed during time. They are improved significantly thought history [3]. With a goal to improve fixation, and to adjust fixation device to the individual fracture types more research is focused to the analysis of mechanical properties of this types of devices using standard theoretical and experimental research usually used in mechanical engineering.

In order to improve necessary tests and make improvements, researchers seek to develop theoretical background of the fixation thematic based on the principles of structural mechanics [4]. Stiffness of the fixation device is defined according to

specific type of load: axial load due to pressure force, bending and torsion [5]. Additionally, for the purposes of defining properties of these devices, researchers rely on force transducers [6]. In the context of biomechanical research, great focus is put on analyzing the influential construction parameters on the fixation device stability. These parameters include stiffness, maximum Von Mises stress for zones of interest as well as bearing capacity of the pin-bone connection, as shown in many experimental studies [7, 8, 9]. In recent period, conducted researches are not only based on experimental investigations, but also on benefits of 3D modeling and numerical analysis. This way, a more complete image and understanding of fixation device behavior is obtained [10, 11, 12].

Main focus is on the stiffness of a device used for fixation [13], because stiffness has the biggest influence on the quality and speed of healing. Usually most of the research are focused on one type of load with a goal to simplify numerical analysis [14, 15].

All of the commercial fixation device, which are in use today, have undergone the biomechanical tests before usage. Biomechanical investigation of the Orthofix fixation device was not

conducted by the means of the exact estimation of its stability under the loads. Main goal of this research is to quantify the mechanical behavior of the standard Orthofix device under the impact of the anterior-posterior (AP) bending. Device is applied to the lower leg for the case of unstable fracture. Design parameters which are taken in consideration for analysis are: device stiffness, values of maximal von Mises and principal stresses and values of displacements at selected points.

DEVELOPMENT OF CAD/FEM MODEL

External fixation device Orthofix was developed after long research and development process carried out by professor Giovanni de Bastiani. He was researcher and professor at University of Verona (Italia) [16]. External fixation device Orthofix have a frame, coupling with spherical joint, four Schanz half pins and dynamic lever. This device is usually called Dynamic axial fixator (DAF). This name is connected to the dynamic lever. Using this lever, it is possible to adjust distance between broken fragments of bone (Figure 1).

For Orthofix device, two types of materials are used, stainless steel and aluminum alloy. Black parts from Figure 1 are manufactured using T6-7075 aluminum alloy. Aluminum is non-toxic, non-magnetic and it does not have corrosion.

Also it is much lighter and cheaper in comparison to the other non-ferrous metals. Parts of the device in grey color (Figure 1) are manufactured using AISI 304 austenite stainless steel. Main advantage of this stainless steel is their resistance to the intercrystalline corrosion. Main disadvantages of this stainless steel is lower value of yield strength due to the lower amount of carbon inside. Mechanical properties of Orthofix device parts are shown in Table 1 [17].

For development of CAD/FEM model of Orthofix device software package CATIA V5 is used. First step is to create CAD models of all parts of the device and then to create assembly. Parts are developed using Part design module of the same software. All parts are connected and assembled using Assembly design module.

Using developed CAD model next step is to create FEM model for all components and for assembly. First step in FEM model development is to create mesh by selecting appropriate finite element. Finite elements of linear and parabolic tetrahedron are used. Linear tetrahedron is used for couplings, spherical joints and screws. Parabolic tetrahedron is used for frame, bone and half pins.

After discretization, next step is to create connections between device parts. Fastened constraints are applied to the places where half pins are connected to the bone (Figure 2a) and contact connections are applied between device parts (Figure 2b).

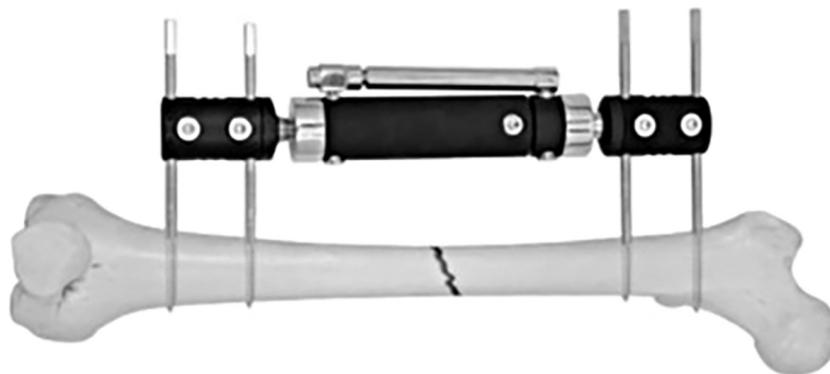


Fig. 1. External fixation device Orthofix

Table 1. Mechanical properties of Orthofix device parts

Part name	Standard marks	Standard marks (EN)	Modulus of elasticity E (GPa)	Poisson coefficient ν	Density ρ (kg/m ³)	Yield strength σ_v (MPa)
Frame	7075-T6	AlZn5MgCu	71.7	0.33	2810	460
Couplings	7075-T6	AlZn5MgCu	71.7	0.33	2810	460
Spherical joints	AISI 304	EN 58E	193	0.29	7900	205
Couplings screws	AISI 304	EN 58E	193	0.29	7900	205
Half pins	1.4441	X ₂ CrNiMo18	196.4	0.3	8000	800

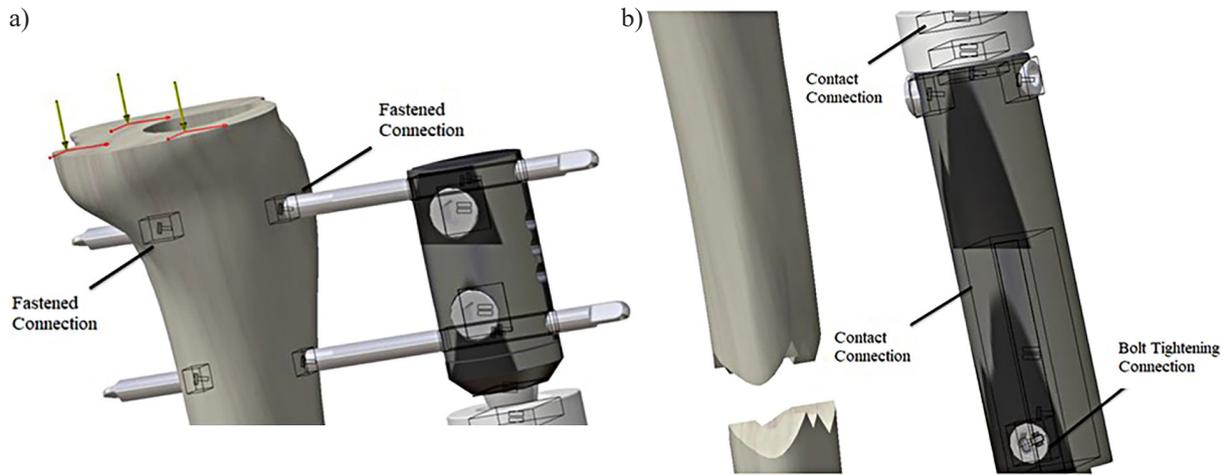


Fig. 2. Connection definition for FEM model, a) fastened connection, b) contact connection

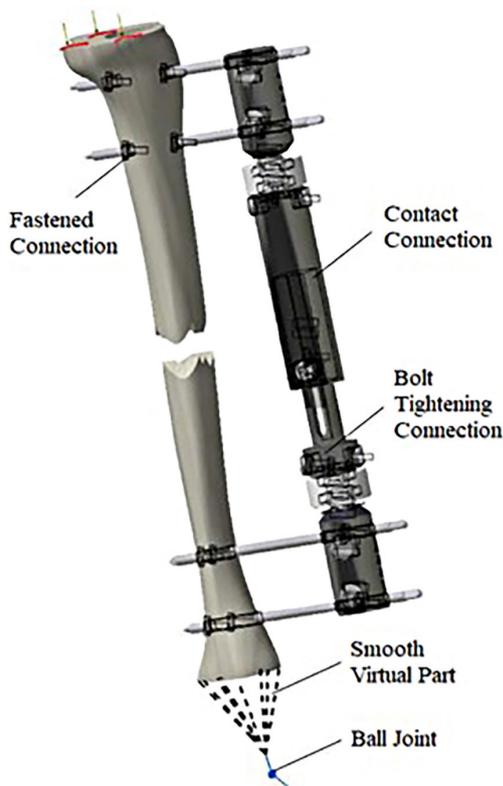


Fig. 3. Ortofix model with defined constraints

After connection definition, next step is to create supports. Supports are constraints in the same time (Figure 3).

Next step in the development process of FEM model is to apply loads. For the case of anterior-posterior bending surface force load is applied at the place of fracture. Force load have a value of 500 N. Two supports are added at the two ends of the bones. Using this arrangement

Table 2. Mechanical properties of bone segment

Property	Value
Longitudinal modulus of elasticity	22900 MPa
Tangential modulus of elasticity	10500MPa
Normal modulus of elasticity	14200 MPa
Poisson coefficient in XY plane	0.29
Poisson coefficient in XZ plane	0.19
Poisson coefficient in YZ plane	0.31
Sliding modulus in XY plane	6480 MPa
Sliding modulus in XZ plane	6000 MPa
Sliding modulus in YZ plane	3700 MPa
Density	1850 kg/m ³

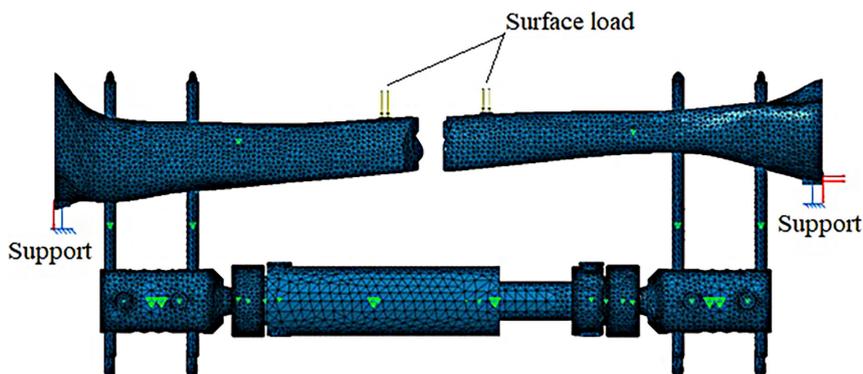


Fig. 4. Loads and support definition

bending moment is created in the plane which correspond with the Orthofix and bone axis's. Supports are connected to the virtual contact parts and to the small flat surfaces created at the bones (Figure 4).

With the load applied, FEM model is finished and it is ready for numerical structural analysis. Final step in FEM model development is to define materials. Materials for Orthofix are defined using data from Table 1. In the case of bone, orthotropic material, needs to be defined. Properties of bone segment are given in Table 2 [18].

DETERMINATION OF STRESS, DISPLACEMENT, AND STIFFNESS

Numerical structural analysis gives values of displacements, principal stress and von Mises stress. Value of equivalent von Mises stress is used very often in solid body mechanics. It can be calculated using following equation [19]:

$$\sigma_e = \sigma_{vm} = \sqrt{3J_2} = \sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]} \quad (1)$$

Displacements are measured at the place of applied load. This values of displacement are used for stiffness calculation. Stiffness is relation between displacements and loads at the place where load is applied.

Stiffness of device according to the AP bending (C_s) can be calculated using following equation [20]:

$$C_s = \frac{F_s}{\delta_s} \quad (2)$$

where: F_s – bending force (N), δ_s – displacement at the place of load (mm).

Stiffness of fracture can be calculated as relation between loads and relative displacement for selected points [21]:

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

Relative displacements of pair ($r_{D(x)}$, $r_{D(y)}$, $r_{D(z)}$) selected points at the end of proximal (upper) and distal (lower) bone segment in x, y, and z direction are defined as: [22]:

$$\begin{aligned} r_{D(x)} &= D_{p(x)} - D_{d(x)} \\ r_{D(y)} &= D_{p(y)} - D_{d(y)} \\ r_{D(z)} &= D_{p(z)} - D_{d(z)} \end{aligned} \quad (4)$$

RESULTS

Figure 6 shows displacement vectors for selected points in the case of maximal loads. Direction and intensity of displacement vector can be

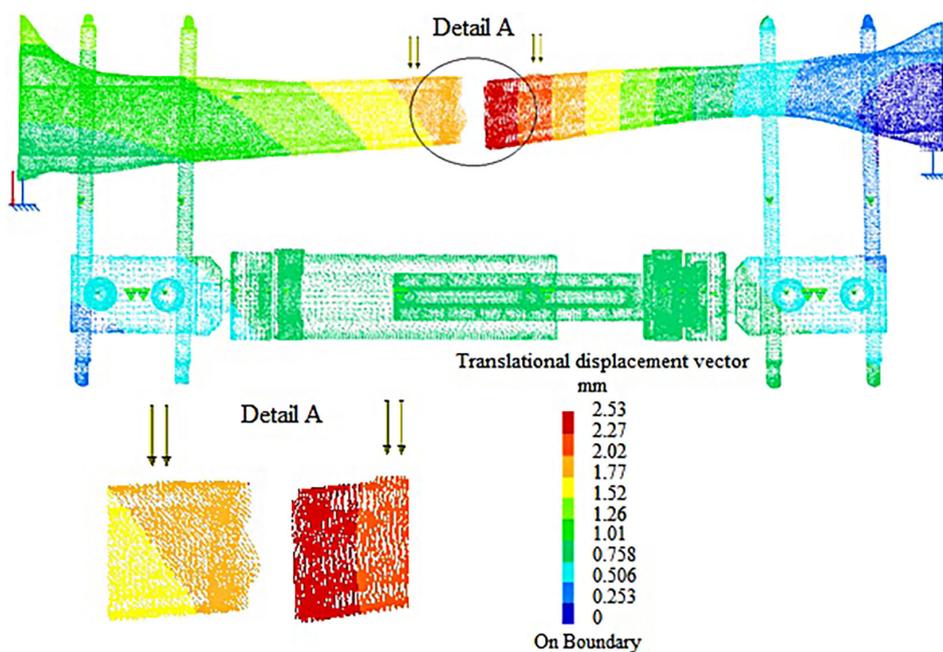


Fig. 5. Vectors of displacement for maximal loads in the case of AP bending

Table 3. Values of displacements for the case of maximal load (AP bending)

Displacement of proximal segment (mm)			Displacement of distal segment (mm)			Stiffness of fracture (N/mm)	Stiffness of fixation device (N/mm)						
Place of load			Place of fracture			Place of load			Place of fracture			C_{pp}	C_p
x	y	z	$D_p(x)$	$D_p(y)$	$D_p(z)$	x	y	z	$D_d(x)$	$D_d(y)$	$D_d(z)$	283.28	235.84
-0.35	2.1	0.01	-0.26	2.51	0.028	1.23	1.44	0.009	1.23	1.57	-0.08		

clearly seen. In addition, it is possible to determine components of displacement vectors (Table 3).

For stiffness analysis in the case of AP bending, middle point at the place of load in the direction of y axis is selected. Using relations (4) relative displacements are calculated for selected points of proximal and distal bone segment for which vector of relative displacement at the place of fracture gives maximal values.

Values of displacements for the case of maximal value of load $F_p = 500N$ are given in Table 3.

In the case of maximal load, maximal displacement is at the place of fracture in lower segment of bone model. Its value is 2.53 mm. Maximal value of displacement on the fixation device is at the ends of half pins. Its value is 1.26 mm (Figure 5).

Stress intensity are depending on the shape of the design (shape of the parts and its placement inside the design). Most critical places on the fixation device are place of contact between screw and spherical joint, between sphere neck and coupling and between sphere and metal shell (Figure 6).

Intensity and direction of principal stresses are analyzed at three critical places for the case of maximal AP bending load (Figure 7). Results are shown using Table 4.

DISCUSSION

Structural analysis is showed that in the case of maximal load, maximal displacement is at the place of fracture in lower segment of bone model. Its value is 2.53 mm. Maximal value of displacement on the fixation device is at the ends of half pins. Its value is 1.26 mm. This values are in the range of allowed values for this type of device. Studies [10, 13] also showed similar displacement values for a similar configuration of the external fixation device loaded with the same load case.

Using values of displacement at the place of fracture, stiffness of the fracture is calculated and its value is 283.28 N/mm. Stiffness of the device is calculated using values of displacements at the

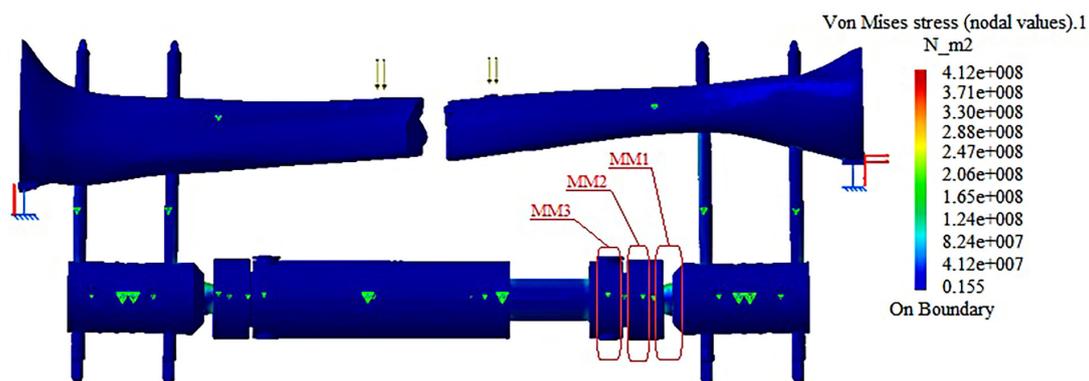


Fig. 6. Von Mises stress for the case of AP bending

Table 4. Values of stresses for the case of maximal AP bending load

Place on the device	Principal stresses at critical places (MPa)						Von Mises stresses at critical places (MPa)	
	MM+			MM-			MM+	MM-
MM	σ_1	σ_2	σ_3	σ_1	σ_2	σ_3	σ_{vm}	σ_{vm}
1	136.41	66.97	43.34	-4.6	-14.09	-92.09	83.79	83.15
2	84.3	12.9	-24.7	2.16	-0.77	-22	95.89	22.6
3	423.05	208.83	205.81	257.81	141.17	122.58	216.12	126.95

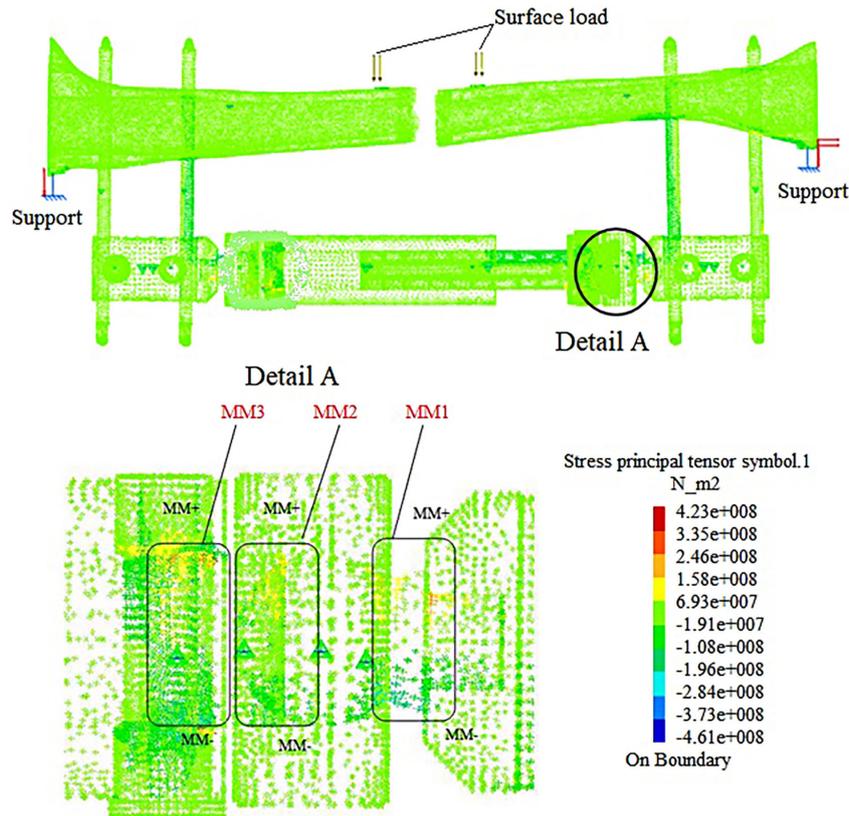


Fig. 7. Principal stress at the critical places on the design

place of load, its value is 235.84 N/mm. Values of stiffness are also in the range of allowed values for this type of design. Studies [10, 20] also showed similar stiffness values for a similar configuration of the external fixation device loaded with the same load case.

During structural analysis for AP bending load it can be noticed that lower bone segment has bigger displacements in comparison to the upper segment of bone. Difference between displacement of upper and lower bone segment is around 1 mm. This is happening because of long screws and bone asymmetry which results with the supports which lies in different level. Lower bone segment is much thinner in comparison to upper bone segment, because of that screw length is shorter in lower bone segment. This have effect on design stiffness and values of displacements. This needs to be tested in future research. It will be good to test is it possible to reduce difference in displacements using different half pins placements or using more half pins.

Intensity and direction of principal stresses are analyzed at three critical places for the case of maximal AP bending load. Selected critical places on the fixation device are place of contact between screw and spherical joint, between sphere neck and coupling and between sphere and metal shell. Bigger

value of stress (216.12 MPa) is at the place number 3 (MM3). This value is lower than value of allowed stress for materials of coupling and half pins.

CONCLUSIONS

With a goal to reduce number of errors during development and design of external fixation device and to reduce number of problems associated with healing process it is necessary to collect all data and important parameters which can have influence on that errors and problems. Important parameters are displacements at the place of fracture and on the device, stiffness of the device, stresses at the critical places, loads of device after its application on the patient. In some cases, other parameters can be taken in consideration also.

In this paper, mechanical stability analysis of external fixation device Orthofix is carried out for the case of anterior-posterior bending. In the first step CAD model of the device is created. Developed CAD model is used to create FEM model. FEM model is used for analysis of the movement of bone at the place of fracture, to analyze mechanical properties of the device and to calculate stiffness of the device.

Taking in consideration all data it can be concluded that external fixation device Orthofix have good mechanical stability for the case of AP bending load. Also there is a possibility to improve device using new advance materials or by device redesign.

REFERENCES

1. Pervan N., Mešić E., Muminović A.J., Delić M., Muratović E., Trobradović M., Hadžiabdić V. Biomechanical Performance Analysis of the Monolateral External Fixation Devices with Steel and Composite Material Frames under the Impact of Axial Load. *Applied Sciences*. 2022; 12(2): 722.
2. Verma V., Pal K.A. Finite Element Investigation on the Design of Mechanically Compatible Functionally Graded Orthopaedic Plate for Diaphyseal Tibia Transverse Fracture. *Composites Part C: Open Access*. 2022; 100228.
3. Paul G.W. The history of external fixation. *Clinics in podiatric medicine and surgery*. 2003; 20(1): 1–8.
4. Koo T.K.K., Chao E.Y.S., Mak A.F.T. Fixation Stiffness of Dynafix Unilateral External Fixator in Neutral and Non-neutral Configurations. *Bio-Med. Mater. Eng*. 2005; 15: 433–444.
5. Drijber F.L.I.P., Finlay J.B., Moroz T.K., Rorabeck C.H. Source of the Slippage in the Universal Joints of the Hoffmann External Fixator. *Med. Biol. Eng. Comput*. 1990; 28: 8–14.
6. Jasinska-Choromanska D., Sadzynski I. Monitoring Technique of Bone Fracture Healing Using External Fixators. *Eng. Trans*. 2003; 51: 255–265.
7. Vossoughi J., Youm Y., Bosse M., Burgess A.R., Poka A. Structural Stiffness of the Hoffmann Simple Anterior Tibial External Fixation Frame. *Ann. Biomed. Eng*. 1989; 17: 127–141.
8. Mešić E., Pervan N., Muminović A.J., Muminović A., Čolić M. Development of Knowledge-Based Engineering System for Structural Size Optimization of External Fixation Device. *Applied Sciences*. 2021; 11(22): 10775.
9. Grubor P., Mitković M., Tanjga R. Značaj biomehaničkih karakteristika spoljnjeg fiksatora u liječenju kominutivnih preloma i koštanih defekata. *Acta Fac. Med. Naiss*. 2002; 19: 211–221.
10. Mesic E., Pervan N., Repcic N., Muminovic A. Research of Influential Constructional Parameters on the Stability of the Fixator Sarafix. In: *Annals of DAAAM for 2012 & Proceedings of the 23 rd International DAAAM Symposium, Vienna, Austria 2012*, 561–564.
11. Pervan N., Mesic E., Colic M., Avdic V. Stiffness analysis of the sarafix external fixator of composite materials. *International Journal of Engineering & Technology*. 2016; 5(1): 20–24.
12. Yilmaz E., Belhan O., Karakurt L., Arslan N. and Serin, E. Mechanical performance of hybrid Ilizarov external fixator in comparison with Ilizarov circular external fixator. *Clin. Biomech*. 2003; 18: 518–522.
13. Pervan N., Mesic E., Colic M., Avdic V. Stiffness Analysis of the Sarafix External Fixator based on Stainless Steel and Composite Material. *TEM Journal*. 2015; 4(4): 366–372.
14. Mešić E., Muminović A., Čolić M., Petrović M., Pervan N. Development and Experimental Verification of a Generative CAD/FEM Model of an External Fixation Device. *Tehnicki glasnik-Technical Journal*. 2020; 14(1): 1–6.
15. Mešić E., Muminović A., Čolić M., Petrović M., Pervan N. Structural Size Optimization of External Fixation Device. *Advances in Science and Technology. Research Journal*. 2020; 14(2): 233–240.
16. De Bastiani G., Apley A.G., Goldberg A.A. *Orthofix external fixation in trauma and orthopaedics*. Springer, London; 2000.
17. Chao E.Y., Hein T.J. Mechanical performance of the standard Orthofix external fixator. *Orthopedics*. 1988; 11(7): 1057–1069.
18. Dehankar R., Langde A.M. Finite element approach used on the human tibia: a study on spiral fractures. *Journal of Long Term Effects of Medical Implants*. 2009; 19(4): 313–321.
19. Pervan N., Mesic E., Colic M. Stress analysis of external fixator based on stainless steel and composite material. *International Journal of Mechanical Engineering & Technology*. 2017; 8(1): 189–199.
20. Mešić E., Avdić V., Pervan N., Repčić N. Finite Element Analysis and Experimental Testing of Stiffness of the Sarafix External Fixator. *Procedia Engineering*. 2015; 100: 1598–1607.
21. Mesic E., Avdic V., Pervan N. Numerical and experimental stress analysis of an external fixation system. *Folia Medica Facultatis Medicinae Universitatis Saraeviensis*. 2015; 50(1): 52–58.
22. Mesic E., Avdic V., Pervan N., Muminovic A. A new Proposal on Analysis of the Interfragmentary Displacements in the Fracture Gap. *TEM Journal*. 2015; 4(3): 270–275.