JOURNAL OF THEORETICAL
AND APPLIED MECHANICS
48, 2, pp. 453-463, Warsaw 2010

PROBLEMS RELATED TO MECHANICS IN THE DESIGN OF EXTERNAL OSTEOSYNTHESIS

Danuta E. Jasińska-Choromańska
Warsaw University of Technology, Department of Mechatronics, Warsaw, Poland
e-mail: danuta@mchtr.pw.edu.pl

The external osteosynthesis is one of the methods of healing bone fractures. The idea of external fixators design consists in inserting into the bone fragments elements, which are coupled outside the limb by an element, called the frame of the fixator, having the fracture set. The external fixation is based on the principle of "load transfer". The design of a new generation of external fixators ought to employ some methods of mechanical analysis. Selected problems related to the modelling and simulation of physical performance of the unilateral external mechatronic orthopaedic fixator-bone system are presented. The majority of works makes use of the rigid finite element method for analysing the orthopaedic device-bone system. The paper presents some problems regarding mechanics applied in the external osteosynthesis design.

Key words: biomechanics, modelling, osteosynthesis

1. Introduction

Over the last century, there took place a fast progress in biomechanics and all sciences connected with this, including evolution of technical sciences employed in biomechanics. A longer lifetime of people is connected with new constructions for implantation and rehabilitation.

Some areas of biomechanics, like external osteosynthesis, including the new generation of external fixators, measure of the healing process of broken bones and active dynamization, are very important for people and will be evaluated in the future very fast.

However, there are problems connected with the design of a new generation of biomechatronic instruments.

The external osteosynthesis with application of external orthopaedic fixators, which has become recently very popular (forerunner of this method was Jean Franscois Malgaine), is a modern method of healing bone fractures. The external fixator is a device adapted for healing bone fractures (Brighton, 1984). The main elements of its structure are the external bearing frame (located outside of the patient's body) and bone implants (bone screws made usually of titanium or implant steel) fixed to the bone fragments. Exemplary configurations of the structure of the bone screws and the external bearing frames are shown in Fig. 1.

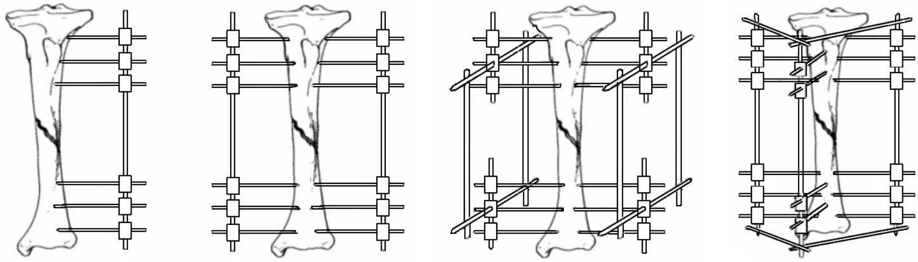

Fig. 1. Configurations of the external fixators (Brighton, 1984)

The new designs regard the postulate of functional healing of fractures. A configuration of the bone screws and the bearing frame defines particular designs of fixators. The external fixators of the new generation are very effective, simple and versatile instruments in the treatment of fractured bones. They are used for stabilization of open fractures in order to keep bone fragments at a right place (Fig. 2).

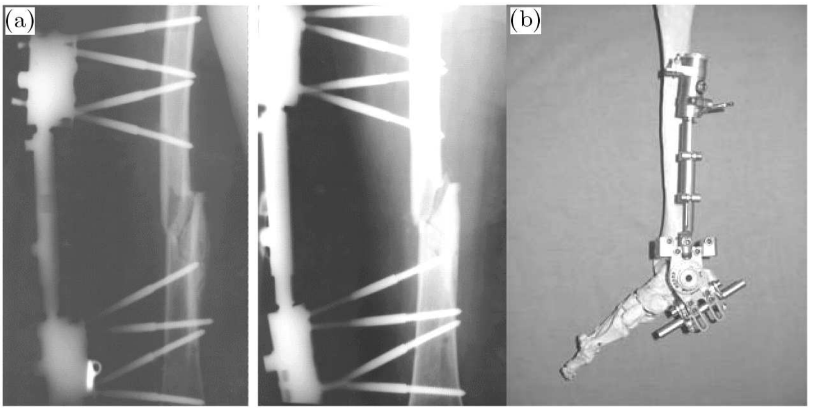

Fig. 2. External fixation: (a) X-ray picture of a fractured bone with the DYNASTAB DK fixator installed; (b) DYNASTAB MECHATRONIKA 2000 – elbow joint (Jasińska-Choromańska *et al.*, 1997)

The fixation is based on the principle of a ”load transfer”. The forces, normally transmitted by the fracture region, are bypassed through the fixator frame and bone interface at the initail stage of treatment. As the fracture callus begins to consolidate, more load is transmitted by the bone fragments. Finally, at the end of the healing process of the bone fragments, all forces are transmitted by the bone itself (Brighton, 1984). Designing a new generation of external fixators by analysing the external fixator-bone system based on application of mechanical methods and models only, seems to be insufficient. The bone and the callus are a live matter whose evolution is ruled by complicated biological processes, moreover the distribution of biological parameters of individual people is very large. It seems that for experiments of biomechanical systems (Chehade *et al.*, 1997), the analysis of structural stability is most important.

Descriptions of new constructions and clinical results are reported in the paper. The parameters of new results have been received from mathematical modelling and computer simulations. The model structure takes into consideration both the nominal model of the system and the mathematical model design technique. The searching inquiry has been limited to discrete models. The latest designs of external fixators make it possible to observe the postulate of functional treatment (Brighton, 1984). This postulate consists in generation of micro-movements in a strictly determined direction (i.e. the axial direction of the bone). These micromovements stimulate the osteogenic processes. Their value should be under adaptive control during the treatment process. It is accomplished by using a dynamization chamber. While regarding the clinical postulate of functional treatment of fractures, a stability concept in purely stochastic technical terms has been employed.

The design of the new generation of these instruments should comprise the modelling, computer simulation, application of CAD/CAM/CAE systems, clinical postulates formulated by phisicians, patients as well as other technical and medical aspects (e.g. measurements of medical and biomechatronic parameters connected with the healing process).

Using microdrives providing micromovements of the bone fractures is one of the most important problems. While connected with measuring appropriate parameters, we can also evaluate the state of bone regeneration. Microdrives may be helpful in overcoming the force that is likely to appear while setting the broken bone and resulting from the muscular tonus.

The new generation of external fixators has been equipped with the measuring system for evaluating the bone healing process, based on intelligent systems.

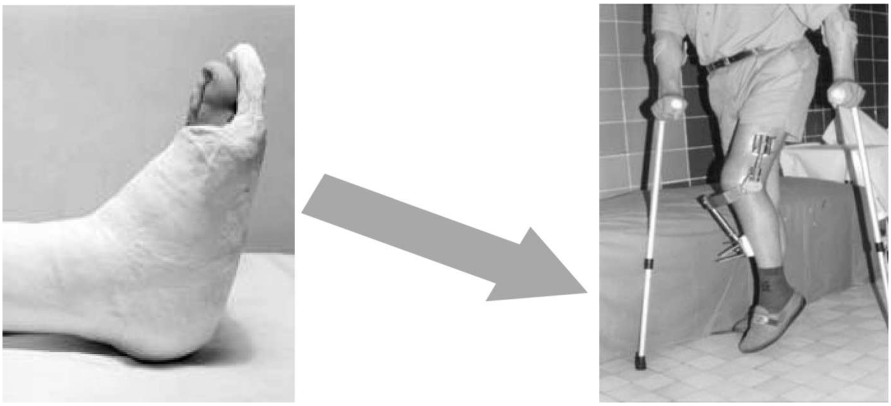

Fig. 3. Changes in construction of external fixators over the history

Problems concerning the modelling, simulation and especially design of new, modern orthopaedic external fixators based on the mechanics are subjects of this paper.

2. Design employing modelling and technical stability

The design process in the area of biomechanics related to external osteosynthesis is connected with identification of the model parameters; first of all, parameters of the tissue. In most cases, the modelling and simulation are strictly limited to mechanical problems, which are usually solved by application of the finite element method. Biomedical systems like fragments of the human body and instruments installed are integral and can be analysed as a biomechanical system (Chehade *et al.*, 1997; Jasińska-Choromańska *et al.*, 1997; Jasińska-Choromańska, 2001; Kołodziej and Jasińska-Choromańska, 2005).

While building a mathematical model of this system, it is required to develop a conceptual model and to describe its properties on this basis. The nominal model is a system made of physical relationships selected on the basis of the identified structure of the machine, plant or process, properties of its individual and external components. A real system can be analysed in accordance with various criteria and phenomena considered; therefore, a number of nominal models, with respect to particular objectives, can be proposed for the system under investigation. A nominal model of the system is shown in Fig. 4. The model with the dynamic chamber for analyses of micromovements of the bone fragments is shown in Fig. 5.

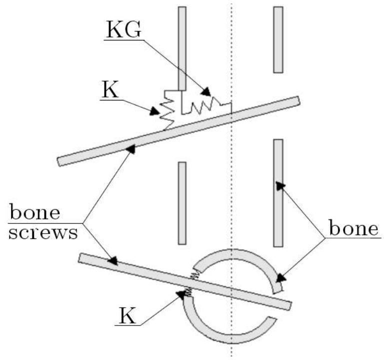

Fig. 4. Nominal model of the external fixator-bone system; K – normal stiffness, KG – tangent stifness

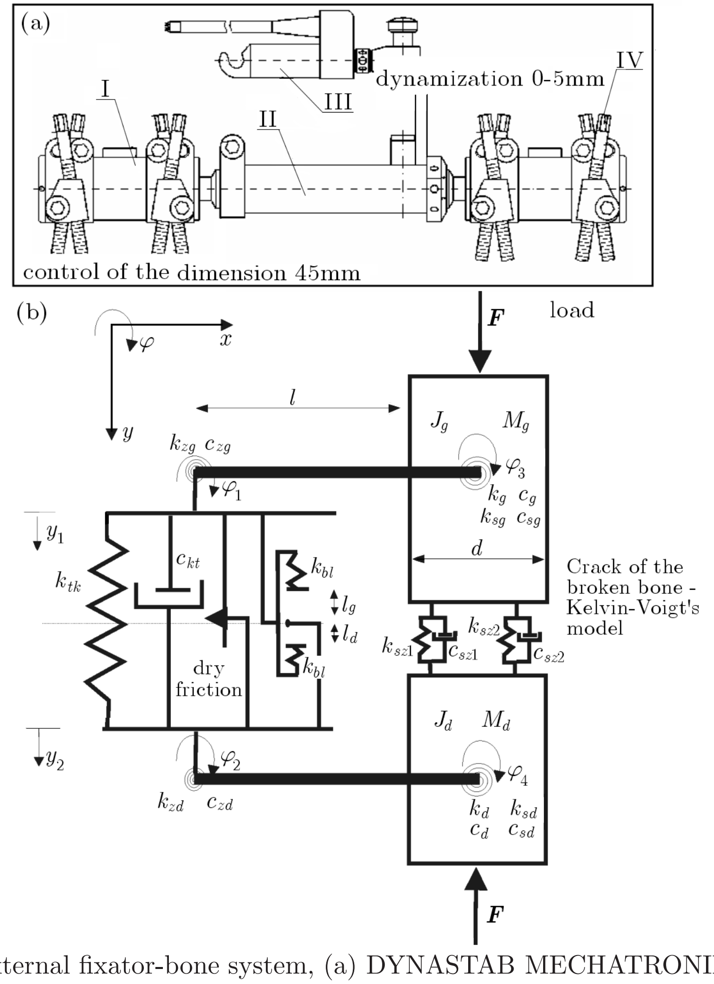

Fig. 5. External fixator-bone system, (a) DYNASTAB MECHATRONIKA 2000 – long bones; (b) nominal model with dynamic chamber (Jasińska-Choromańska, 2001; Jasińska-Choromańska and Choromański, 2002)

The nominal model has been represented by a Lagrange II-kind equation.

The general form of the equations of motion of the fixator-bone system for dynamic analysis can be expressed as

$$\mathsf{A}\ddot{\boldsymbol{q}} + \mathsf{B}\dot{\boldsymbol{q}} + \mathsf{C}\boldsymbol{q} + \boldsymbol{F}_N = \boldsymbol{Q}_w \tag{2.1}$$

where

$\mathsf{A},\mathsf{B},\mathsf{C}$	–	matrix of damping, stiffness and moment of inertia, respectively
$\boldsymbol{F}_N$	–	vector of forces produced by the flexible parameters
$\boldsymbol{Q}_w$	–	coercions outputs affecting the system contact area in the nominal model of the screw–bone system (Fig. 4)
$\boldsymbol{q}$	–	vector, $\boldsymbol{q} = [y_1, y_2, \varphi_1, \varphi_2, \varphi_3, \varphi_4]^\top$.

The nominal model with the dynamization chamber for dynamic analysis is shown in Fig. 5.

For the linear part of the system, the equation for kinetic energy is

$$E_k = \frac{1}{2}\Big\{M_g\Big[\dot{y}_1 + \dot{\varphi}_1\Big(l + \frac{1}{2}d\Big)\Big]^2 + M_d\Big[\dot{y}_2 + \dot{\varphi}_2\Big(l + \frac{1}{2}d\Big)\Big]^2 + J_g\dot{\varphi}_3^2 + J_d\dot{\varphi}_4^2\Big\} \tag{2.2}$$

Potential energy is

$$\begin{aligned} E_p = \frac{1}{2}\Big\{&k_{tk}(y_1 - y_2)^2 + k_{zg}\varphi_1^2 + k_{zd}\varphi_2^2 + k_g(\varphi_3 - \varphi_1)^2 + k_d(\varphi_4 - \varphi_2)^2 + \\ &+k_{sz1}\Big[\Big(y_1 + \varphi_1 l - \varphi_3\frac{d}{2}\Big) - \Big(y_2 + \varphi_2 l - \varphi_4\frac{d}{2}\Big)\Big]^2 + \\ &+k_{sz1}\Big[\Big(y_1 + \varphi_1(l + d) + \varphi_3\frac{d}{2}\Big) - \Big(y_2 + \varphi_2(l + d) + \varphi_4\frac{d}{2}\Big)\Big]^2 + k_{sg}\varphi_3^2 + k_{sd}\varphi_4^2\Big\} \end{aligned} \tag{2.3}$$

Rayleigh's function is

$$\begin{aligned} R = \frac{1}{2}\Big\{&c_{tk}(y_1 - y_2)^2 + c_{zg}\varphi_1^2 + c_{zd}\varphi_2^2 + c_g(\varphi_3 - \varphi_1)^2 + c_d(\varphi_4 - \varphi_2)^2 + \\ &+c_{sz1}\Big[\Big(y_1 + \varphi_1 l - \varphi_3\frac{d}{2}\Big) - \Big(y_2 + \varphi_2 l - \varphi_4\frac{d}{2}\Big)\Big]^2 + \\ &+c_{sz1}\Big[\Big(y_1 + \varphi_1(l + d) + \varphi_3\frac{d}{2}\Big) - \Big(y_2 + \varphi_2(l + d) + \varphi_4\frac{d}{2}\Big)\Big]^2 + c_{sg}\varphi_3^2 + c_{sd}\varphi_4^2\Big\} \end{aligned} \tag{2.4}$$

The Lagrange function is represented by the following equation

$$L = E_k - E_p \tag{2.5}$$

The used Lagrange equations of the second kind are in the form

$$\frac{d}{dt}\Big(\frac{\partial L}{\partial \dot{q}_i}\Big) + \frac{\partial L}{\partial q_i} + \frac{\partial R}{\partial \dot{q}_i} = Q_i \tag{2.6}$$

For examplem matrix $\mathbf{A} = \{a_{ij}\}$ of stiffness

$$
\begin{aligned}
&a_{11} = -a_{12} = -a_{21} = a_{22} = k_{tk} + k_{sz1} + k_{sz2} \\
&a_{13} = -a_{14} = -a_{23} = a_{24} = a_{31} = -a_{32} = -a_{34} = -a_{41} = a_{42} = -a_{43} = \\
&\qquad = k_{sz1}l + k_{sz2}(l+d) \\
&a_{15} = -a_{16} = -a_{25} = a_{26} = a_{51} = -a_{52} = -a_{61} = a_{62} = \frac{d}{2}(-k_{sz1} + k_{sz2}) \\
&a_{33} = k_{zg} + k_{sz1}l^2 + k_{sz2}(l+d)^2 + k_g \\
&a_{35} = a_{53} = -k_{sz1}\frac{ld}{2} + k_{sz2}\frac{(l+d)d}{2} - k_g \\
&a_{36} = a_{45} = a_{54} = a_{63} = k_{sz1}\frac{ld}{2} - k_{sz2}\frac{(l+d)d}{2} \\
&a_{44} = k_{zd} + k_{sz1}l^2 + k_{sz2}(l+d)^2 + k_d \\
&a_{46} = a_{64} = -k_{sz1}\frac{ld}{2} + k_{sz2}\frac{(l+d)d}{2} - k_d \\
&a_{55} = k_g + k_{sg} + k_{sz1}\Big(\frac{d}{2}\Big)^2 + k_{sz2}\Big(\frac{d}{2}\Big)^2 \\
&a_{56} = a_{65} = -k_{sz1}\frac{d^2}{4} - k_{sz2}\frac{d^2}{4} \\
&a_{66} = k_d + k_{sd} + k_{sz1}\Big(\frac{d}{2}\Big)^2 + k_{sz2}\Big(\frac{d}{2}\Big)^2
\end{aligned}
$$

3. Simulation results and clinical verification – examples

The tests were performed on the nominal model presented in Fig. 6 and a model developed in compliance with the method presented above. The system has been loaded along three directions.

The results of exemplary simulation are shown in Figs. 7 and 8. These figures illustrate examples of the translation and rotation of the bone fragments with and without dynamization. From these figures, we concluded that the system with the dynamization features more advantageous properties. Clinical observations confirm such a conclusion. Osteolysis (Fig. 7) plays an important role here, and it has significant influence on the fixation realized by means of the external fixators.

The positive effect of "spatial tent" configuration of the bone screws on the system rigidity with respect to the linear configuration is evident. The following data were assumed for the optimal system: $\alpha = 20$ degrees arc, $\beta_1 = 17$ degrees arc, $\beta_2 = -17$ degrees arc (the angles of axial configura-

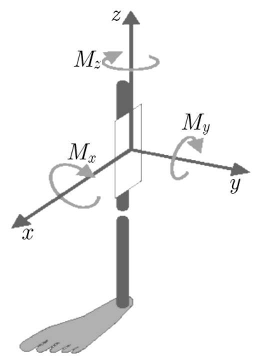

Fig. 6. Orientation of the reference frame

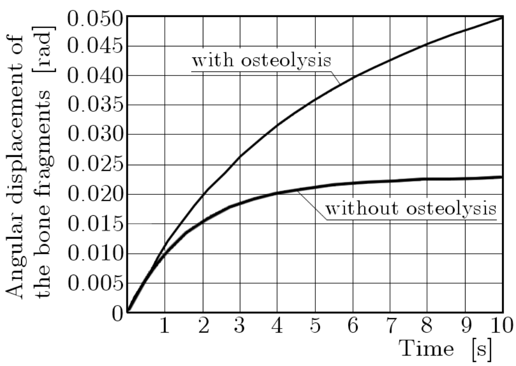

Fig. 7. Results of computer simulation: angular displacements of the bone fragments

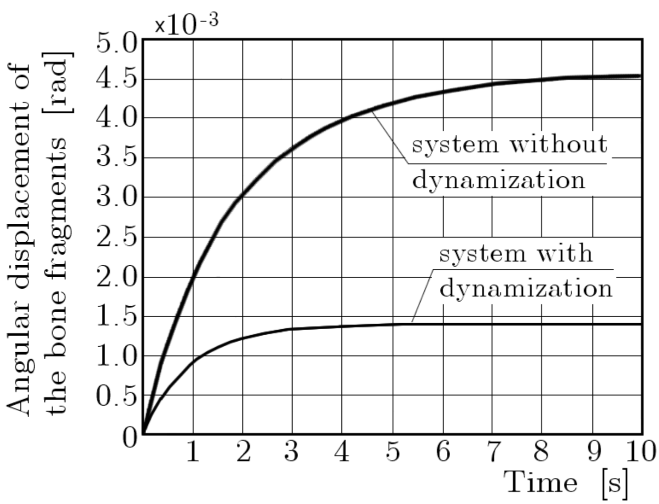

Fig. 8. Angular displacements of the bone fragments

tion of the bone screws within the bones). The limitations imposed on the values of angles resulted from the fact observed in clinical practice that the bigger the increase of the angle β values (Jasińska-Choromańska, 2001, 2005; Jasińska-Choromańska and Choromański, 2002), the bigger increase of tangential stresses within the contact regions.

All computer simulations were clinically verified at the hospital (in Warsaw).

From the point of view of dynamization in the external osteosynthesis, the dynamic parameters are connected with the technical stability method, where the objective function is represented by the equation

$$Q = \int\limits_0^T \Big[\sum_{i=1}^{N} q^2_{i(i\neq k,l)} + (P_{allow} - |q_k - q_l|)^2\Big]\, dt \tag{3.1}$$

Some example of the performed analysis is presented in Fig. 9. The main point of the optimization was the diameter of the bone screws, and after simulation it was estimated to have a value of ca. 6.7 mm.

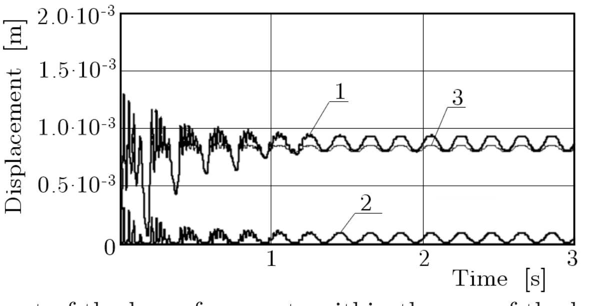

Fig. 9. Displacement of the bone fragments within the gap of the broken bone after optimization; load $F = 400$ N; 1 – all displacements of the bone in the crack along the axial direction; 2 – partial displacement of the bone screws; 3 – partial displacement of the crack

The computation of the objective function was based on the nominal model (Jasińska-Choromańska, 2001) represented by equation (2.1).

4. Conclusions

The research methods introduced in the paper were used for carrying out simulation studies of the external fixator-bone system. The results provide some information about rotations and translations of the bone fragments. They were fully confirmed in the clinical practice.

The preliminary results obtained are very promising. Computer design techniques like modelling and simulation presented in this paper were used for designing mechatronic unilateral external fixators. It seems that the simplified form of the employed model of the external fixator-bone system determines its properties with a satisfactory accuracy from the point of view of engineering and medical needs. For the time being, the clinical experience is promising and confirms the correctness of the techniques of computer design. Further research works are being continued with regard to these issues.

References

1. Brighton C.T., 1984, *Principles of Fracture Healing, Part I, The Biology of Fracture Repair*, Instr. Course Lect.

2. Chehade M.J., Pohl A.P., Pearcy M.J., Navana N., 1997, Clinical implications of stiffness and strength changes in fracture healing, *The Journal of Bone and Joint Surgery*, **79-B**, 1

3. Jasińska-Choromańska D., 2001, Modelling and simulation in the of design unilateral external orthopaedic fixators, *Science Works of Warsaw University of Technology*, **186**, Warsaw

4. Jasińska-Choromańska D., 2005, Some problems of XXI century biomechanics, *Machine Dynamics Problems*, **29**, 3, 33-50, ISSN 0239-7730

5. Jasińska-Choromańska D., Deszczyński J., Karpiński J., et al., 1997, Mechatronic orthopaedic external fixators, *XVIII Symposium on Fundamentals of Machine Design*, Kielce-Ameljówka, Conference Proc.

6. Jasińska-Choromańska D., Choromański W., 2002, Modelling unilateral external fixators with dynamic chamber, *Acta of Bioengineering and Biomechanics*, **4**, 1, 763-764

7. Kołodziej D., Jasińska-Choromańska D., 2005, Special kinds of diagnosis in the external osteosynthesis, *3rd European Medical and Biological Engineering Conference – EMBEC'05*, Prague (Czech Republic), proc. CD, ISSN 1727-1983

Wybrane zagadnienia mechaniki w projektowaniu ortopedycznych stabilizatorów zewnętrznych

Streszczenie

Stabilizacja zewnętrzna jest jedną z metod leczenia złamanych kończyn. Konstrukcja stabilizatorów zewnętrznych składa się z ramy nośnej umieszczonej po zewnętrznej stronie złamanej kończyny oraz wkrętów kostnych zamocowanych w odłamach złamanej kończyny i zablokowanych jednocześnie w ramie nośnej. Ideą konstrukcji stabilizatorów zewnętrznych jest „przenoszenie obciążenia" podczas procesu zrostu złamanych odłamów kostnych przez ramę nośną, a tym samym odciążenie szczeliny zrostu kostnego. W projektowaniu stabilizatorów nowej generacji wykorzystywane są wybrane zagadnienia mechaniki, które umożliwiają analizę układów biomechanicznych, takich jakim w prezentowanym artykule jest system stabilizator zewnętrzny-odłam kostny. Artykuł prezentuje zastosowanie wybranych zagadnień mechaniki w projektowaniu ortopedycznych stabilizatorów zewnętrznych nowej generacji.

Manuscript received June 4, 2009; accepted for print October 27, 2009