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Modeling and simulation of physical performance of a External Unilateral Mechatronic Orthopaedic Fixator - Bone system

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Abstract

Restricted element study of the fracture healing by external fixation device was investigated. The analyses were performed under an axial and variable loaded boundary conditions. The effect of different fracture size and different distance between bone and the external fixator device on the stress distribution was investigated. The results show that stresses in the external fixator device are highest at the beginning of the fracture healing process, and are gradually decreasing with the time of the treatment. The analyses were carried out using the commercial package CATIA P3 V5R11. This allowed to build a three-dimensional model more similar to the geometrical architecture of the long bone as well as of the external fixator. Three-dimensional restricted element model also allowed a collection of more realistic results. However, the accuracy of the results depends not only on the quality of the model geometry but also on the material properties assigned to the model components. It also depends on the accuracy in the simulation of the finite element model and the optimized mesh generation.

I. INTRODUCTION

MANY different fixation systems are available to treat fractures of long bones. Fixation systems used in the early phase of treatment allow for an early full weight bearing after fracture stabilization However, fractures which have low stiffness values can not be loaded by the patient. Goodship and Kenwright (1985) showed that early daily periods of cyclic micro-movement increase the rate of healing because of the early formation of a periosteal callus. According to C.Kershaw, J.Cunnigham and J.Kenwright studies [1], rapid fracture healing is expected when the interfragmentary movement can be controlled using external fixation systems. As there are many fixation systems and each system imposes its own mechanical environment like strength and stiffness inside the fracture gap there are many possibilities of a more precise diagnostics for the fracture healing. Stiffness of the fracture determines how much weight the patient will be able to bear on the fractured limb. In the early phase of treatment, most of the loads applied to the bone (as a result of vertical posture of human body) are transferred to the fixator's frame. Simultaneous measurements of weight bearing and fracture stiffness in patients treated with external fixation gives the opportunity to monitor the progression of weight bearing as a measure of recovery of of the fracture stiffness.

The paper presents a method of monitoring the bone fracture healing process based on the measurements of weight bearing by External Unilateral Mechatronic Orthopaedic Fixator – Dynastab (Fig.1). The External Unilateral Mechatronic Orthopaedic Fixators are classified as fixator's of new generation designed for strength, versatility, and visibility for trauma and reconstructive surgery.

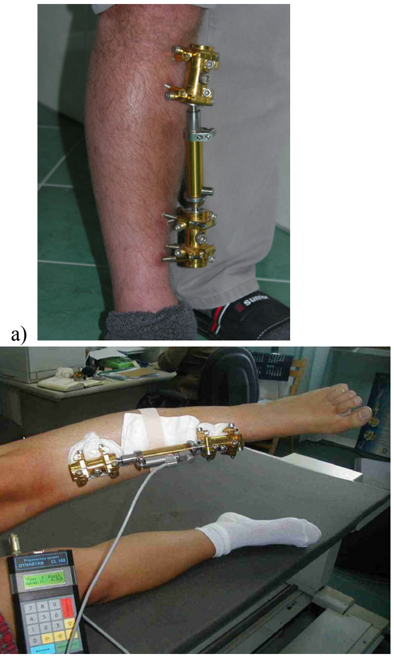
a)
b)

Fig.1. Fixator Dynastab Mechatronika 2000 – clinical application; a) general application, b) with measurement system

Dynastab's measurement system allows an evaluation of the weight bearing as well as the stress distribution during fracture healing. In other words, evolution of stress can help to estimate the current stiffness of healed fracture.

Some of the benefits and features of External Unilateral Mechatronic Orthopaedic Fixator – Dynastab are as follow:

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- It allows for micro-movement inside the fracture gap in precise defined direction
- It makes the bone reposition much easier; it means it is easy to install by using ball joints and self-threated screws
- It allows the user to define the distances between the connecting fixator's frame and the bone
- It has the angular separation of the screws. Versatile screw placement options give higher stiffness even in the case of osteolisis processes.
- It has the procedure for measuring the compression forces on the fixator's frame, that occur under the load applied to the bone and depend on the mechanical properties of the fracture, it can be performed using tensometers, which is a cheap and simple method
- It has high stiffness; The stiffness of unilateral external fixator is secured by higher than usual diameter of the screws as well as by the stiffness of fixator's frame. From the clinical point of view the higher frame stiffness reduces undesirable translational and angular displacements
- Its frame is made from titanium, however the carbon fiber are also used (assure lightness). Screws are made from biomaterials.

The changes in the mechanical properties of the fracture gap during healing process have an impact on weight bearing by fixator's frame as well as by the bone. As the fracture is healed over the time, the correlation between load applied to the External Orthopaedic Fixator – Bone system and load transferred to the fixator's frame as well as to the bone can be defined as follows:

$$m(t) = \frac{F(t)_f}{F(t)_{total}} = \frac{F(t)_f}{F(t)_{fl} + F(t)_b} \qquad (1)$$

where:

$F(t)_f$ – weight bearing by fixator's frame

$F(t)_b$ - weight bearing by bone

$F(t)_{total}$ – weight bearing by External Orthopaedic – Fixator - Bone system

m(t) factor (refer to (1)) gives information's about the healing progress during the time of treatment, when *m(t)* factor is decreasing, it means more weights is beard by the bone (Fig.2, Fig.3).

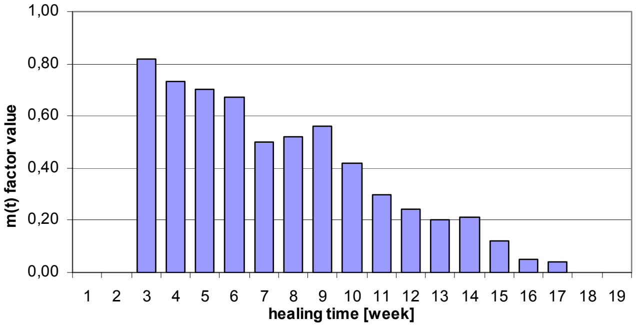

Fig.2. Patient with transverse tibial fracture; no compression (1mm fracture gap); 100N load applied to a broken limb

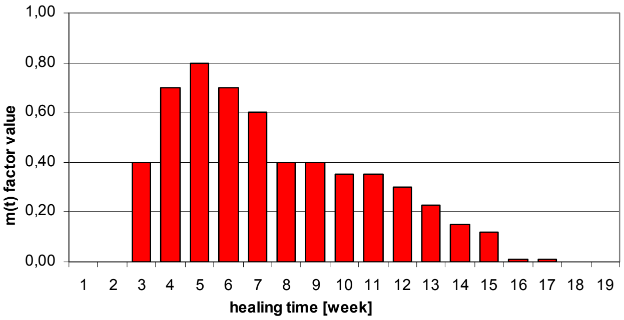

Fig.3. Patient with transverse femur fracture, compression; 100N applied to a broken limb

As it can be seen from the figures above the time of healing varies with the applied type of treatment. It can either be with or without the compression. At the early stage of healing process, most of the applied loads are beard by the bone due to the compression. Afterwards, when fracture gap is shaping and callus is forming, the load which is transferred to the fixator's frame decreases. This technique requires a period of treatment of about 4 months.

II. METHOD

Mechanical performance of the external fixation system can be evaluate by means of restricted element method. Due to the complex geometry of external fixation system, the restricted elements method seems to be the most adequate method to find out the stress patterns of long bone stabilized by fixation system.

A. *Solid model*

The three-dimensional model of proximal, distal bones and fracture gap was created. For the purpose of simplicity, the proximal as well as the distal bone employed in the model were defined as hollowed cylinders with 28 mm proximal diameter, 14 mm distal diameter and 120 mm of length. Hollow cylinder is stiffer and stronger in bending then a solid one[7]. An external fixator was modeled as a separate solid where the frame and the screws were filled as inside cylinders. The external fixator was virtually inserted into. The axial distance between the bone and the external fixator was defined as 50, 60 and 70 mm, which corresponds to 26, 36, 46 mm for setting external fixator away from the outer boundary of the bone. The geometrical elements which have no effect on the model stiffness were ignored. All contact parts were defined as deformable parts and all except the fracture gap, were assumed to be fully fixed (zero displacement) to each other.

B. *Finite element model*

As the fracture site is exposed to an axial loading, a variable load configuration was used. Also as mentioned above different regions were introduced in the model enabling the definition of different isotropic material properties as we assumed:

- the bone properties closely relates to the cortical bone properties, ie. Young's modulus E = 2e+10 [N/m^2], Poisson's ratio 0,3
- for the external fixator, stainless steel was employed, (Young's modulus E = 2e+11 [N/m^2], Poisson's ration 0,266)
- different material properties (based on Young's modulus values) attributed to fracture gap, refers to the fact that healing process of the bone occurs slowly over months. Material properties for fracture gap based on the values given by D. Lacroix and P.J Prendergast [2].

Table.1. Material properties applied for fracture zone

	Young's modulus[N/m^2]	Poisson's ratio
granulation tissue	2E+05	0,167
fibrous tissue	2E+06	0,167
cartilage	1E+07	0,167
immature bone	1E+09	0,3
mature bone	6E+09	0,3
cortical bone	2E+10	0,3

Analyses were also performed for different conditions in the fracture zone (it means the size and geometrical conditions of the fracture) as they are representative of different types of fracture. The fracture was created as a 0,5; 1; 2; 3 mm gap between proximal and distal bone with incline of 0°, 15°, 30° and 45°.

In this way, taking into account mechanical and geometrical conditions, the evolution of stress before, during and after fracture healing were studied.

The solid model was performed to 3D restricted element model which automatically created restricted elements mesh grid. Four-noded linear tetrahedral elements were used to build up the mesh of the proximal, distal bones, fracture gap and external fixator. Mesh grid was defined in the global and local systems with absolute sag - 1mm. In places were the model geometrical continuity was disrupted (ie. holes in the bone, frame joints, fracture zone) the mesh grid was build. This (the use of smaller elements) follows from our objective, which was to investigate the stress distribution at the fracture gap as well as in the contact regions.

III. RESULTS

A. Stiffness and stress analysis

The stress distribution can be classified according to the fracture healing timeframe. At the early stages when cartilage is formed from granulation tissue, the most weight is beard by the external fixator, so the stress distribution is: (Fig.4, Fig.6):

a) high stress (critical zone), where the stress magnitude reaches over 1,17e+006 N/m2. This occurs in the regions of the frame joints, frame and also in the distal and proximal bones. The highest stress value of 9,38e+007 N/m2 occurred in the upper fixator's frame joint.
b) medium stress, where the stress magnitude was between 1,17e+006 N/m2 and 1,29e+04 N/m2, which occurred in the region of the proximal and distal parts of the fixator's frame, the screws and in the region of contact between the bone and the screws
c) low stress, where the stress magnitude was less than 1,29e+04 N/m2, which occurred in the region of bone and fracture zone. The minimum stress value of 2,19e+002 N/m2 occured in the fracture gap.

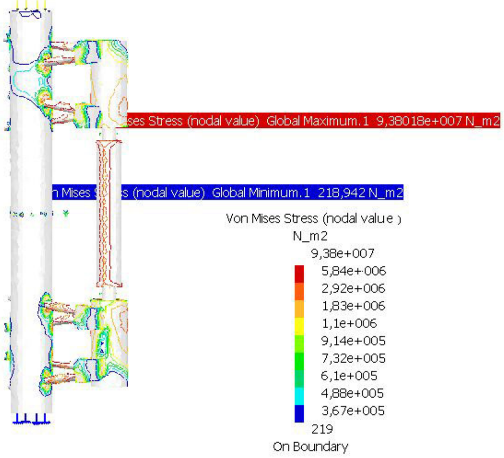

Fig. 4. Stress distribution at the beginning of the fracture healing process (granulation tissue at fracture gap). Load –150N, 1mm transverse fracture gap, 60 mm distance between bone and fixator's frame

At the later stages of healing process, during which cortical bone is formed from immature bone, the bone progressively transfers the loads and the three different zones can also be distinguished (Fig.5, Fig.6):

d) high stress (critical zone), where the stress magnitude reaches over 7,92e+05 N/m2, which occurred in the regions of fracture gap. The max stress value was 1,25e+07 N/m2.
e) medium stress, where the stress magnitude was between 7,92e+05 N/m2 and 2,9e+05 N/m2, which occurred especially in the contact regions.
f) low stress, where stress magnitude was less than 2,9e+05N/m2, which occurred in the region of the upper and lower fixator's frame sides with min stress value of 1,05e+03 N/m2.

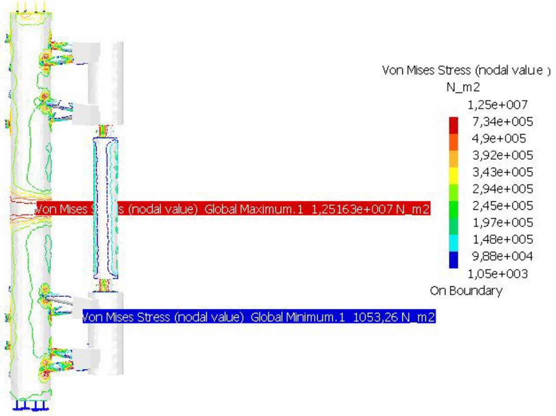

Fig. 5. Stress distribution at the end of the fracture healing process (cortical bone at fracture gap). Load –150N, 1mm transverse fracture gap, 60 mm distance between bone and fixator's frame

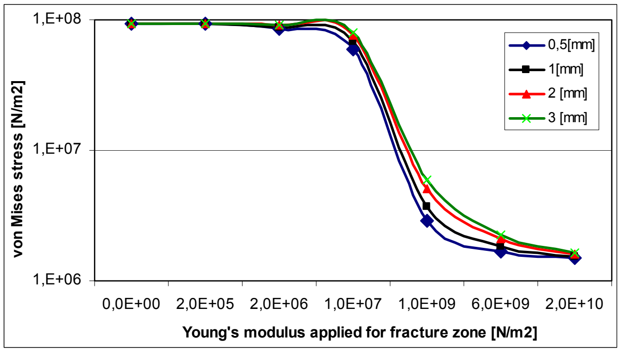

Fig. 6. Max von Mises stress distribution as a function of Young's modulus applied to the fracture zone. Parameter: fracture gap size.

B. Conclusion

- The von Mises stress can give information about the stage of fracture healing (fig.6) and the non linear characteristic of von Mises stress at the external fixator's frame can be defined during fracture healing process.
- The stress distribution at the end of the fracture healing process is highest in the bone and lowest in the external fixator. When this happens, it means fracture was healed and fixator can be removed.
- The maximum stress value difference exists at the stage of cartilage to immature bone formation.
- The change in the fracture size does not result in any significant changes in the maximum von Mises stresses at the external fixator's frame (Fig.6). That is why for the fracture size of 0,5mm, a variable load analysis vs stress distribution at external fixator's frame were performed (Fig. 7).
- Applied load has proportional linear impact on von Mises stress during granulation tissue, fibrous tissue and cartilage stages of fracture healing. In the other phases, von Mises does not depend on the applied load (Fig.7).

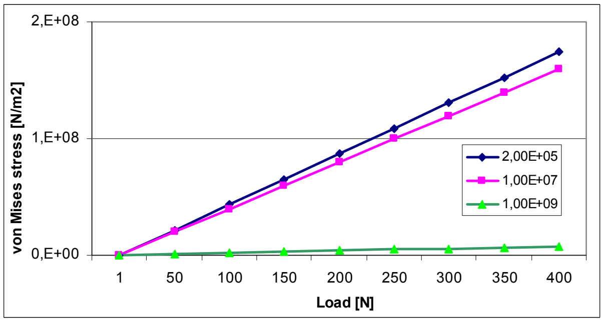

Fig.7. von Mises stress distribution at the fixator's frame as a function of applied load.Parameter: Young's modulus applied to the fracture zone

- Fracture inclination has a little impact on stress value at fixator's frame with value of 0,1% at the stage of cartilage or immature bone formation (Fig. 8, Fig.9).

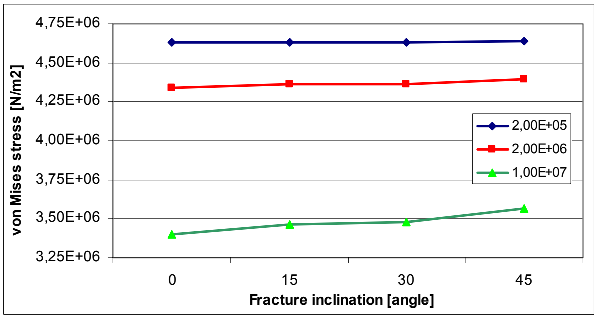

Fig.8. von Mises stress distribution as a function of fracture inclination; Parameter: Young's modulus for granulation tissue, fibrous tissue and cartilage

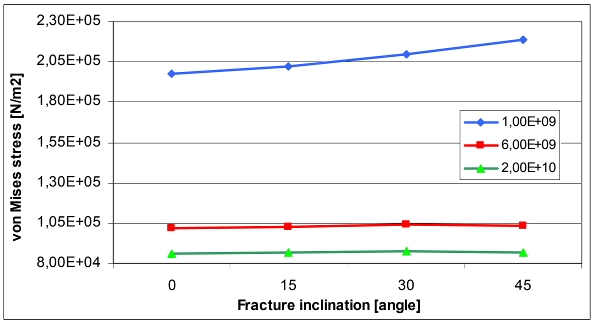

Fig. 9. von Mises stress distribution as a function of fracture inclination: Parameter: Young's modulus for immature, mature and cortical bone

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