ON ENGINEERING VERIFICATIONS OF EXTERNAL AND INTERNAL FIXATORS FOR TRAUMATOLOGY AND ORTHOPAEDICS

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Summary

In this article the authors draw attention to the possibilities of treatment for complicated bone fractures. They present their own design, laboratory tests and numerical solutions (i.e. strength analyses and reliability assessments) of the various types of internal and external fixators applied in traumatology and orthopaedics (i.e. intended for fractures of limbs, pelvis and calcaneus). The new design of external fixators is based on the development of Ilizarov and other techniques (i.e. shape and weight optimization based on composite materials, application of smart materials, nanotechnology, low x-ray absorption, antibacterial protection, patient comfort, reduction in the duration of surgical treatment, and cost). Similarly, the new intramedullary nail C-NAIL (i.e. an example of an internal fixator) is intended for minimal-invasive fixation of intraarticular calcaneal fractures.

Keywords: external and internal fixators, traumatology, orthopaedics, design, numerical modelling, experiments, verification

1. INTRODUCTION

Changes in lifestyle, military conflicts, increased population age, accidents, the development of endoprosthetics etc. are connected with the increased occurrence of many types of unstable, opened, periprosthetic and other types of complicated bone fractures in recent years; see Fig. 1 and 2.

Fig. 1. X-ray of Rorabeck type II fracture (periprosthetic) – lateral view

Every bone fracture leads to a complex tissue injury involving the bone and the surrounding soft parts.
There exist several possibilities for treatment of these fractures, each involving possible complications. For this reason, complicated fractures represent an important therapeutic problem due to their specific and individual character. Among the general risk factors we can include possible infections, osteoporosis, rheumatoid arthritis, treatment with corticosteroids, and naturally other diseases which may affect healing processes in patients. There is still continuing debate over which treatment option is optimal for such patients. There is no consensus on the optimal technique to be used, but logically it must be minimally invasive in order to decrease mortality and morbidity. Stable osteosynthesis obtained by minimal invasive techniques assures more rapid fracture union. Therefore, treatment of fractures is a challenge for the surgeon; see for example references [1] to [8].

Usually there is no consensus on the surgical management of fractures (external fixation versus internal fixation etc.). However, this text focuses on the treatment of complicated fractures – see Fig. 1 and 2 – treated via external fixation (for examples for the limbs and pelvis see Fig. 1 and 3) and internal fixation (for the calcaneus see Fig. 4) and their engineering verification via numerical methods and laboratory testing.

The study is based on the authors’ work in cooperation between the VŠB - Technical University of Ostrava, the Trauma Centre of the University Hospital in Ostrava, the Pardubice Regional Hospital and the MEDIN a.s. company; see e.g. references [2], [9] to [12], [14], [15] and [17].

2. EXTERNAL FIXATORS
(MEDICAL PERSPECTIVE)

External fixators can be applied in traumatology, surgery and orthopaedics for treatments such as open and unstable (complicated) fractures (see Fig. 2, 3 and 4), limb lengthening, deformity correction, consequences of poliomyelitis, foot deformities or hip reconstructions (see Fig. 1 etc.). Hence, external fixators can be used for treatment of humans and animals; see e.g. Fig. 5, 6 and 7 (one case of treatment of a patient in Ostrava), reference [2].
Fractures of the acetabulum occur when the head of the femur is driven into the pelvis. This is caused either by a blow on the side or by a blow at the front of the knee, usually in a dashboard injury, when the femur may also be fractured.

External fixators intended for the treatment of limbs are presented in Chapter 3; external fixators intended for the treatment of this pelvis and its acetabulum are presented in Chapter 4.

3. EXTERNAL FIXATORS FOR LIMBS (ENGINEERING VERIFICATION)

References [2], [10] and [11] present a way of designing new external fixators intended for treatments of limbs. These fixators are in line with new trends in medicine (i.e. X-ray invisibility of the outer parts of fixators – see explanation in Fig. 8; antibacterial protection based on nanotechnology; new materials and new design; weight optimization; patient comfort; reduction in the duration of surgical treatment; cost etc. – see Fig. 9).

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Fig. 8 Typical problems with high X-ray absorption (The outer parts of fixators are usually made of metal – i.e. titanium, duralumin, stainless steel – which are visible in X-ray diagnostics. Sometimes surgeons must repeat X-ray diagnostics (from different points of view) during the operation, because it is difficult to see the broken limbs. Therefore it is important to make the outer parts of fixators X-ray invisible, which shortens operating times and reduces radiation exposure for patients and surgeons.)

Fig. 9 Design of external fixators a) based on metals (old design, heavier, expensive, etc.), b) based on reinforced polymers (new design, lighter, cheap, more patient-friendly etc.)

In order to increase the antibacterial potency of external fixators, kaolinite/nanoTiO2 composite was laboratory prepared and its antibacterial activity tested with respect to daylight irradiation time. Kaolinite/nanoTiO2 composites with 20 and 40 wt% of TiO2 were laboratory prepared, dried at 105°C and calcined at 600°C. The calcination caused transformation of kaolinite to metakaolinite and origination of the metakaolinite/nanoTiO2 composite. X-ray powder diffraction, Raman and FTIR spectroscopic methods revealed titanium dioxide only in the form of anatase in all evaluated samples (non-calcined and calcined) and also transformation of kaolinite to metakaolinite after the calcination treatment. Scanning electron microscopy was used as a
method for characterization of the morphology and elemental composition of the studied samples. A standard microdilution test was used to determine the antibacterial activity using four human pathogenic bacterial strains (Staphylococcus aureus, Escherichia coli, Enterococcus faecalis, and Pseudomonas aeruginosa). A lamp with a wide spectrum bulb simulating daylight was used for induction of photocatalysis. The antibacterial assays found all the samples to have antibacterial potency with different onset of the activity; calcined samples exhibited antibacterial activity earlier than non-calcined samples. No significant difference in antibacterial activity of the samples for different bacterial strains was observed. For more information see [15] to [17].

Numerical modelling and laboratory experiments (based on previous techniques; see references [2], [10], [11] and [15]) provide support during the research and design process, and represent very important parts of the solution; see e.g. Fig. 10 and 11 (i.e. applications of FEM) and Fig. 12, 13 and 14 (i.e. applications of experiments in our laboratory – preclinical research).
According to the laboratory experiments (i.e. preclinical research) and numerical modelling (strength analyses), the verifications of external fixators for limbs are sufficient. Therefore, these are reliable and can be used for treatment of patients. For more information see reference [15].

4. EXTERNAL FIXATORS FOR THE PELVIS AND ACETABULUM (ENGINEERING VERIFICATION)

At the VŠB – Technical University of Ostrava (Ostrava, Czech Republic), two designs of external fixators intended for treatment of pelvis and acetabulum fractures (see Fig. 3) were designed and tested (i.e. an old version denoted as 'Option 1' and a new, modern version denoted as 'Option 2'); see Fig. 15 and references [9] and [15].

Option 1" (see Fig. 15) is fully metallic (this is the old design which does not satisfy the new demands presented in Chapter 3 – see e.g. the problems mentioned in Fig. 8).

By contrast, "Option 2" (see Fig. 15) is only partly metallic (this is the new design which satisfies the new demands presented in Chapter 3). There are composite rods made of carbon fibres which are X-ray invisible; see the problems mentioned in Fig. 8.

The new types of external fixators for treatment of fractures of the pelvis and its acetabulum were tested in the laboratory at the VŠB – Technical University of Ostrava (Ostrava, Czech Republic); see references [9] and [15] and Fig. 16.

The experiments were focused mainly on the stiffness and reliability of the whole system of the fixator and its interaction with the pelvis (i.e. measurements at particular points – pulling the hip bone outwards from the acetabulum after the repositioning of pelvis fragments). The maximum value of force 100 N denotes overloading (i.e. the tests were performed under conditions of excessive loading, which is not usual during the treatment of patients); see Fig. 17.

The basic information about the boundary conditions is presented in Fig. 17. It defines mechanical contacts with friction between the brackets and titanium pipes ('Option 1') or between the brackets and
composite rods ("Option 2") and between brackets and Schanz screws.

Schanz screws are embedded in the pelvis and its acetabulum in drilled holes. Their attachments are modelled by elastic supports (i.e. by Winkler’s foundation; see points 'A' and 'B' in Fig. 17). The elastic support (defined via the modulus of foundation \( K/\text{Nm}^3/ \); see Fig. 17) is applied in the radial and axial directions on the surface parts of the Schanz screws. This is a reasonably good and widely used simplification of the real complicated interaction between screw and bone; see ref. [9]. The elastic foundation and its applications in engineering are explained in more detail in [18] to [22].

The results, for example see Fig. 18, Tab. 1 and references [9] and [15], show a very important improvement in the new design ("Option 2") compared with the older design ("Option 1"). In Tab. 1, the symbols ‘\( \circ \)’ or ‘\( \bullet \)’ mean the positive or negative aspects in the design.

![Fig. 18 “Option 2” - FE modelling of external fixator for the pelvis and acetabulum (equivalent stresses for tensile loading 100 N)](image-url)

<table>
<thead>
<tr>
<th>ATTRIBUTES</th>
<th>OPTION 1</th>
<th>OPTION 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design:</td>
<td>old</td>
<td>new</td>
</tr>
<tr>
<td>Material:</td>
<td>titanium, stainless steel</td>
<td>carbon fibre, titanium, stainless steel</td>
</tr>
<tr>
<td>Added antibacterial protection:</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>X-ray invisible:</td>
<td>no</td>
<td>partly yes</td>
</tr>
<tr>
<td>Weight of external fixator</td>
<td>decreasing</td>
<td></td>
</tr>
<tr>
<td>Stiffness of external fixator:</td>
<td>increasing</td>
<td></td>
</tr>
<tr>
<td>Maximum von Mises stresses /MPa/:</td>
<td>97.1</td>
<td>85.6 – decreasing; see Fig. 18</td>
</tr>
<tr>
<td>Maximum total deformation /mm/:</td>
<td>5.74</td>
<td>4.32 - decreasing</td>
</tr>
<tr>
<td>Patient comfort:</td>
<td></td>
<td>improvement</td>
</tr>
<tr>
<td>Reliability assessment:</td>
<td></td>
<td>improvement</td>
</tr>
<tr>
<td>Easy to assemble:</td>
<td>the same</td>
<td></td>
</tr>
</tbody>
</table>

The results of experiments fit well with numerical modelling.

According to the laboratory experiments (i.e. preclinical research) and numerical modelling (strength analyses), the verifications of external fixators for the pelvis and its acetabulum are sufficient. Therefore, these can be used for treatment of patients. For more information see reference [15].

5. **INTERNAL FIXATOR FOR THE CALCANEUS (MEDICAL PERSPECTIVE)**

Internal fixation is an operation in orthopaedics and traumatology that involves the surgical use of implants for the purpose of repairing a bone. Usually, an internal fixator may be made of stainless steel or titanium. Types of internal fixators include bone screws and metal plates, pins, rods, Kirschner wires and intramedullary devices such as the Kuntscher nail and interlocking nail etc.
This chapter focuses mainly on the C-NAIL – see Fig. 19 to 22 and references [12] to [14] – i.e. the intramedullary nail for minimal-invasive fixation of extraarticular and intraarticular (Sanders I – IV, Joint Depression type and Tongue type) calcaneal fractures; see e.g. Fig. 4. The principle is to use the nail to stabilize the four to five main fragments of the fractured calcaneus in conjunction with up to seven interlocking screws, thus creating angular stable fixation. The maximum level of stability is achieved by fixing the sustentacular fragment towards the nail with two interlocking screws guided by a very precise aiming device.

6. INTERNAL FIXATOR FOR THE CALCANEUS (ENGINEERING VERIFICATION)

The C-NAIL offers several benefits; see Fig. 23:

1. Implementation of a minimally invasive approach (repositioning of fragments necessitates just a small lateral approach from the apex of the lateral ankle toward the base of the metatarsal V – about 3 cm – and only a few mini-incisions for the introduction of the nails and screws).

2. High stability of fixation (high stability of the implant, providing a very good fixation of the fragments).

3. Minimal risk of infection (in comparison with other techniques the MEDIN C-NAIL displays a lower risk of infection).

4. Simple and accurate application (the principle of the surgical technique for application of the MEDIN calcaneal nail is based on commonly used operating procedures and draws on their advantages).

Numerical modelling for the C-NAIL rested in a broken calcaneus was performed; see e.g. Fig. 24, 25 and 26 (i.e. applications of FEM).
Experimental tests were also performed for the C-NAIL; see reference [14].

According to the laboratory experiments and numerical modelling (strength analyses), the verifications of the C-NAIL are sufficient. Therefore, the C-NAIL can be used for treatment of patients. For more information see reference [14].

7. CONCLUSION

Complicated fractures represent an important therapeutic problem due to their specific and individual character.

According to the results and applications presented in this paper (i.e. some examples of external and internal fixators for the treatment of limbs, the pelvis and its acetabulum, and the calcaneus), the verifications of these fixators are sufficient. Therefore, these fixators can be used for treatment of patients.

This paper has reported on new ways of designing external and internal fixators, based on the results of previous research. The new designs and materials of fixators will satisfy the ambitious demands of modern traumatology, surgery, and economics. According to the results, the improvements in the design of fixators for the treatment of fractures are evident. The VSB – Technical University of Ostrava, together with the University Hospital of Ostrava and the Pardubice Regional Hospital, are cooperating with the Czech company MEDIN a.s. (Nové Město na Moravě, Czech Republic). Therefore, not all results could be published in this paper due to reasons of confidentiality.

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References


