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Numerical method in biomechanical analysis of intramedullary osteosynthesis in children

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Analysis and modelling

ABSTRACT

Purpose: The paper presents the biomechanical analysis of intramedullary osteosynthesis in 5-7 year old children.
Design/methodology/approach: The numerical analysis was performed for two different materials (stainless steel – 316L and titanium alloy – Ti-6Al-4V) and for two different fractures of the femur (1/2 of the bone shaft, and 25 mm above). Furthermore, the stresses between the bone fragments were calculated while loading the femur with forces derived from the trunk mass. In the research the Metaizeau method was applied. This method ensures appropriate fixation without complications.
Findings: The numerical analysis shows that stresses in both the steel and the titanium alloy nails didn't exceed the yield point: for the stainless steel $R_{p0,2,}$min = 690 MPa and for the titanium alloy $R_{p0,2,}$min = 895 MPa.
Research limitations/implications: The obtained results are the basis for the optimization of mechanical properties of the metallic biomaterial.
Practical implications: On the basis of the obtained results it can be stated that both stainless steel and titanium alloy nails can be aplied in elastic osteosythesis in femur fractures in children.
Originality/value: The obtain results can be used by physicians to ensure elastic osteosythesis that accelerate bone union.
Keywords: Numerical techniques; Biomaterials; Intramedullary nails

1. Introduction

Increasing pace of life and development of technology cause dramatic increase of accidents victims. Unfortunately, not infrequently children are the major group who meet with an accident. The basic injury in this group is a limb fracture.

In these cases an effective method of the bone fragment stabilization is the intramedullary osteosynthesis that enable a new fracture treatment without bone union complications.

In the last decade small invasive techniques of intramedullar stabilization became a recognized method of treatment of long bone fractures in children. Indications for application of these methods with reference to the type of fracture and age were widened. Increase of intramedullary fixations in children was caused by an improvement of biomaterials [1-5]. Basic advantages of intramedullary fixation are [6-25]:

- shortening of the bone union time,
- decrease of the danger of infection,
- there is no need to open the fracture site,
- nails are placed from the little lateral and medial incision that allows to protect the haematoma and periosteum which presence is essential for the bone union,
- improvement of the fixation stability,
- shortening of the bone union time,
- short time of hospitalization: two days after the humeral, forearm and tibia fractures, five days after the femoral bone fracture,elasticity of nails allows to obtain both compression

- and distraction which are very favourable in the bone union process,
- significantly lower cost of treatment in comparison to the traditional method.

Long term research on the selection of the rigid or elastic intramedullary nails proved that because of the presence of a temporary cartilage in long bones the rigid nails osteosynthesis can not be applied. Therefore to stabilize long bone fractures in children the elastic nails are applied.

The idea of the elastic osteosynthesis consists in the introduction into the medullar canal the opposite curvature nails – fig. 1. This way of stabilization enables three points of contact between nails and the medullar canal – fig. 2. As a result of that while loading the bone micromovements that accelerate the bone union are stimulated. This is a little invasive method that ensures a fast fracture healing [6,23].

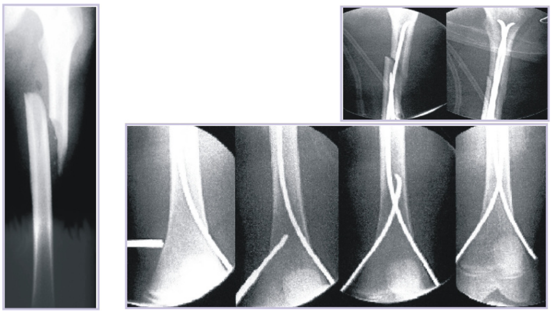


Fig. 1. Elastic intramedullary nails inserted in femur – retrograde approaches [20]

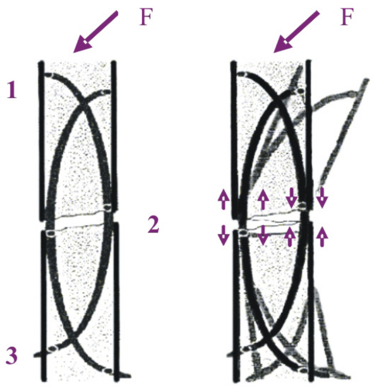


Fig. 2. Axial forces enabling the deformation of the union site: a – free point contact, b – micromovement on the fracture site, F – loading forces [7]

Metaizeau' method is the most frequently applied in clinical practice because due to a very good biomechanical effect in a bone union zone. Very important are stresses in implants made of different biomaterials [26-32]. The stresses can't exceed the yield point: for the stainless steel $R_{p0,2}$,min = 690 MPa and for the titanium alloy $R_{p0,2}$,min = 895 MPa.

2. The aim of the work

The aim of the work was the numerical analysis of a child femur – intramedullary nails system for 5-7 year old children. In order to evaluate stresses in the nails and in the contact plane between bone fragments as well as displacements of the upper fragment, the finite element method was applied. The influence of the fracture gap location on stresses in the nails was analyzed. Furthermore, stresses between bone fragments depending on the applied metallic biomaterial were also analyzed.

3. Method

3.1. Geometrical models of femur - intramedullary nails

In accordance with antropometric features of children bones, taking into consideration the most frequent femur fractures, two models were analyzed:

- *model 1* – a two-fragment, oblique (angle γ=40°) fracture in ½ of the bone shaft, fracture gap was equal to 0,8 mm – fig. 3a,
- *model 2* – a two-fragment, oblique (angle γ=40°) fracture 25 mm above the ½ of the bone shaft, fracture gap was equal to 0,8 mm – fig. 3b.

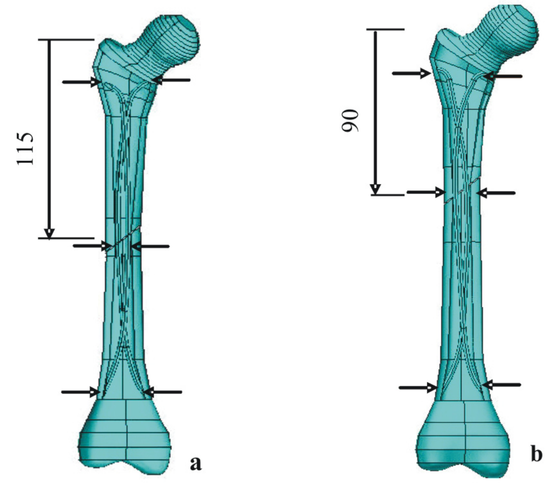


Fig. 3. The models of femur – intramedullary nails: a – the model 1, b – the model 2, → contact between bone and nails

For the given geometric features of bones the intramedullary nails of 2,5 mm diameter were selected. In modeling the retrograde approach, often used in children fractures, was applied. In accordance with the Metaizeau method the three point contact between the medullary canal and the nail was simulated: first – in the site of the greater trochanter, second – in the fracture gap, third – in the site of the nail insertion. In order to reach the appropriate stability of the system the nails were merged with the bone in the mentioned contact points.

3.2. Discrete model of femur - intramedullary nails

In order to perform the finite element analysis a meshing of the geometrical model of the implant was done. The SOLID 95 finite element was used – fig. 4. This element allows to take into consideration physical nonlinearities and large displacements.

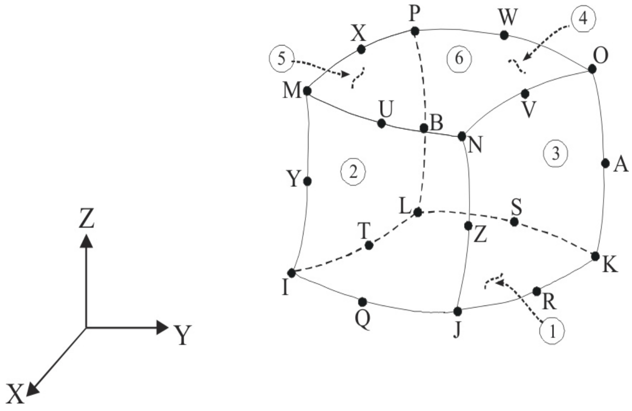
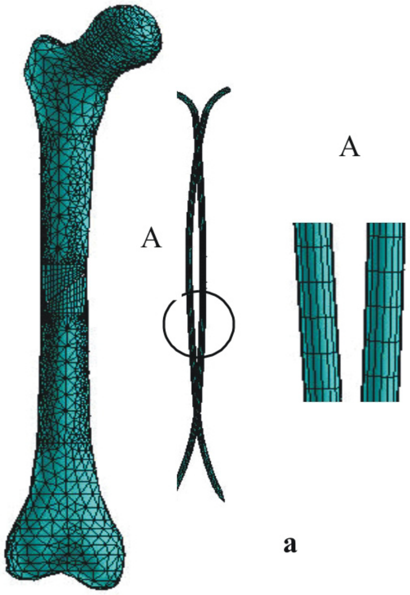


Fig. 4. The SOLID95 finite element

Discrete models of the fixation are presented in fig. 5a and fig. 5b.



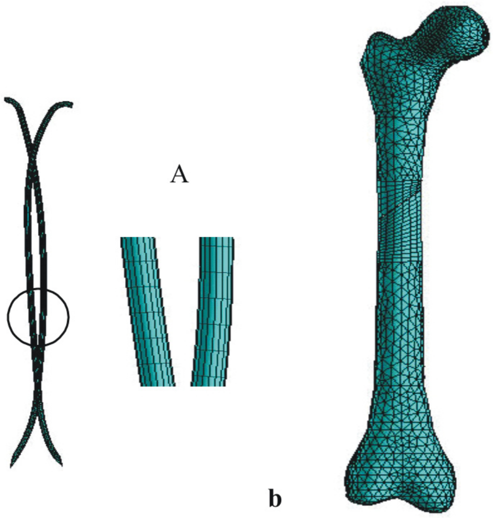


Fig. 5. Discrete models of: a – the model 1, b – the model 2

3.3. Boundary conditions

For the prepared intramedullary nails – femur system the following boundary conditions were set:

- distal metaphysis was immobilized (all degrees of freedom were taken away),
- both models were loaded with the following forces: R – on the femur head, and M – from muscles (gluteus), – fig. 6.

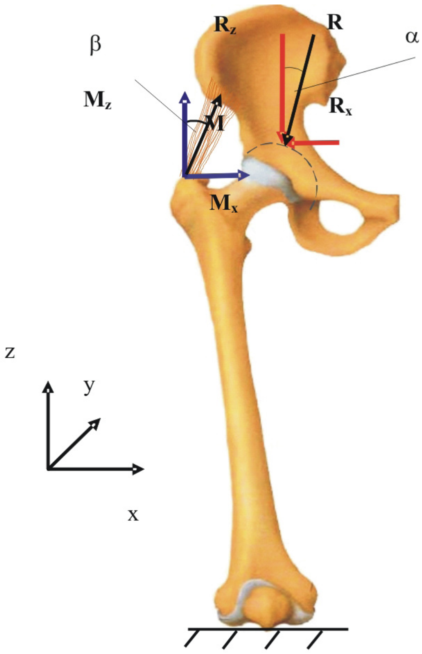


Fig. 6. Loading scheme of model

- the analysis didn't take into consideration the activity of ligaments and muscles (which stabilize the fracture site in real conditions),
- the bone material was set as linear elastic, isotropic and homogeneous,
- displacements of the upper fragment were analyzed in the frontal plane (along the x axis) – fig. 7,

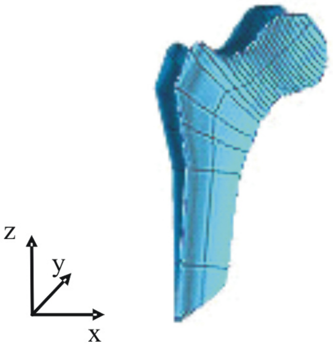


Fig. 7. Displacement of the upper fragment

- maximum stresses in the nails were calculated for two biomaterials: stainless steel – 316L and titanium alloy – Ti-6Al-4V,
- the following mechanical properties of bones and nails were set:
  - mechanical properties of bone [33]:
    - E=18600 MPa,
    - ν= 0,33.
  - mechanical properties of nails:
    - stainless steel [34]:
      - E=200000 MPa,
      - ν= 0,33,
      - $R_{p0,2}$,min=690 MPa,
    - titanium alloy [35]:
      - E=110000 MPa,
      - ν= 0,33,
      - $R_{p0,2}$,min=895 MPa,

4. Results

On the basis of the numerical analysis, stresses in bones in the contact site as well as in the intramedullary nails were calculated. Differences in stress values in the characteristic points of the nails were connected with the location of the fracture gap, the nail – bone interface and the applied biomaterial. During loading the upper fragment was characterized only by the axial movement because of the displacement limitations in other planes.

Differences in displacements of the upper fragment for two applied materials were small. The increase of the displacement of 0,1 mm for the steel nails was observed for the fracture in ½ of the bone shaft. However, for the fracture 25 mm above the ½ of the bone shaft the increase was equal to 0,06 mm – fig.8. It can be stated that both applied materials can be successfully used for this type of fixation.

Compressing stresses in the contact site between the fragments – fig. 9 and 11 were lower for the titanium nails and didn't exceed the value of 34 MPa for the model 1 and 36 MPa for the model 2. For the steel nails the increase of stresses was observed. For the model 1 the local stresses were insignificantly higher, however in both cases the stresses didn't exceed the value of 40 MPa. So, the stresses didn't exceed the maximum, limiting value of 200 MPa [32]. Above this value a decohesion of the bone tissue is observed – tab. 1

Table 1.
Stresses in nails and in the frature gap

	Maximum stresses in nails, MPa		Compresion stresses in the fracture gap, MPa	
	Cr-Ni-Mo	Ti-6Al-4V	Cr-Ni-Mo	Ti-6Al-4V
Model 1	1700	1189	39.106	33.319
Model 2	1499	1072	39.324	35.729

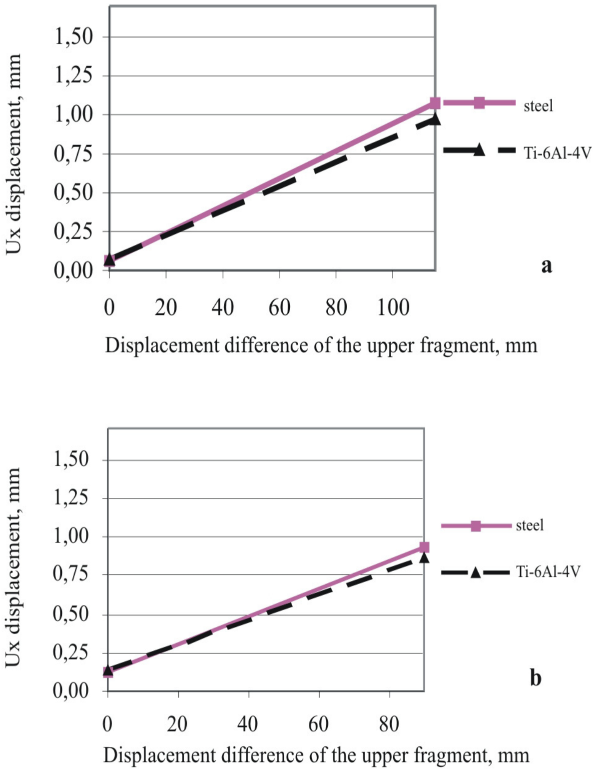


Fig. 8. Displacement difference of the upper fragment for loading 250 N: a – model 1, b – model 2

Local exceeding of the maximum stress was observed in contact site between the bone and the nail. Higher values of stresses were observed in the steel nails. But stresses in the real system were much lower because of the possibility of displacements – fig. 10 a,b and 12 a, b.

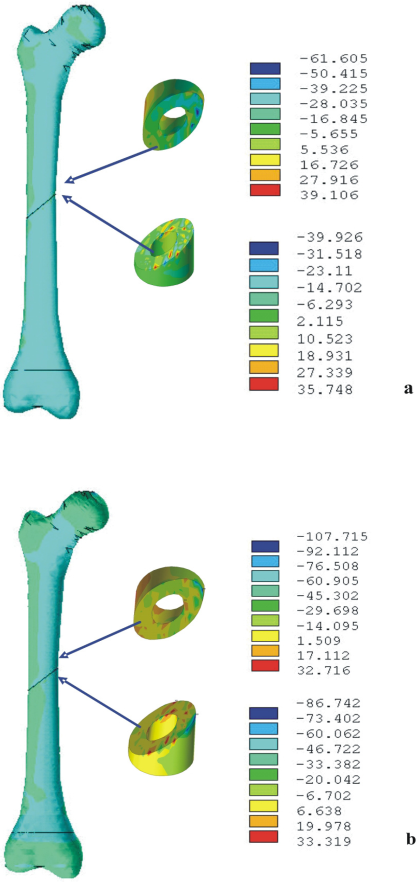


Fig. 9. Stress distribution (MPa) in the fracture gap – model 1: a – stainless steel, b – titanium alloy

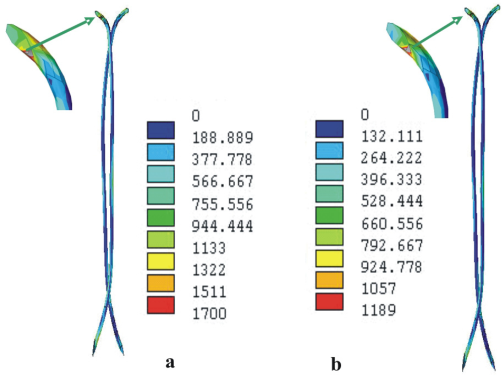


Fig. 10. Stress distribution (MPa) in nails, model 1: a – stainless steel, b – titanium alloy

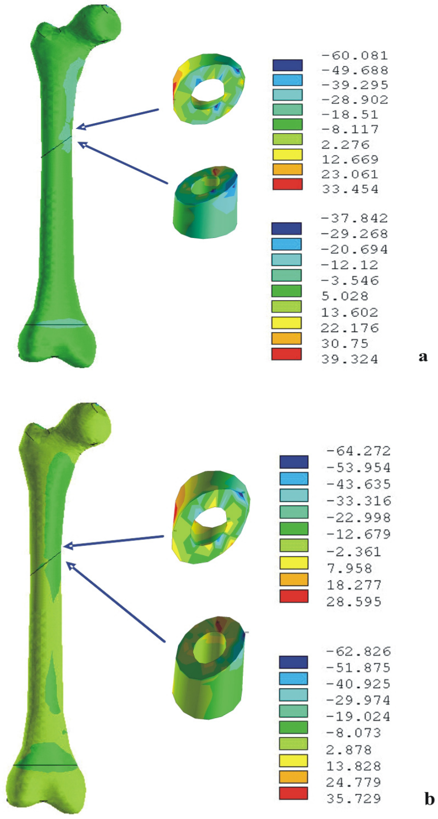


Fig. 11. Stress distribution (MPa) in the fracture gap – model 2: a – stainless steel, b – titanium alloy

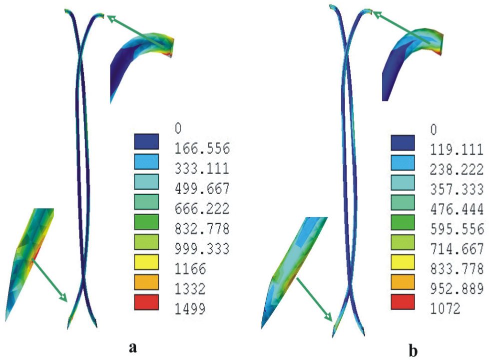


Fig. 12. Stress distribution (MPa) in nails, model 2 : a – stainless steel , b – titanium alloy

5. Cocnlusions

The numerical analysis shows that stresses in both the steel and the titanium alloy nails didn't exceed the yield point: for the stainless steel $R_{p0,2}$,min = 690 MPa and for the titanium alloy $R_{p0,2}$,min = 895 MPa [34,35].

However the local increase of stresses in the nail – bone contact site was observed. The stresses in titanium nails are lower than in steel ones. The maximum local stresses for the model 1 were equal to 1700 MPa for the steel nails and 1189 MPa for the titanium nails. For the model 2 the stress values were respectively 1499 MPa and 1072 MPa. In both cases the maximum limiting stress in the fracture gap (200 MPa) wasn't exceeded. It shows that no decohesion occurred in the bone tissue. On the basis of the obtained results it can be stated that lower stresses are obtained for the model 2, that is for the fracture 25 mm above the ½ of the bone shaft.

In order to analyze the intramedullary nails – femur system extreme boundary conditions were set. These conditions appear to be very rare. The stress analysis in the nails was the basis for the selection of mechanical properties of the biomaterials. Maximum stresses localized in the contact area between the nail and the bone, are not reached while loading of the limb because of a displacement possibility of fragments in the elastic range of the analyzed biomaterials.

Taking the real system (cramp of muscles and ligaments) and stresses in the nails obtained in the numerical analysis into consideration, it can be concluded that healing process will be correct, without excessive rotation of the fragments. The micromovements of the fragments in the fracture gap will accelerate the bone union.

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