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Mathematical model of mechanical testing of bone-implant (4.5 mm LCP) construct

Lucie Urbanová[1], Iva Blažek-Fialová[1], Robert Srnec[1], Jan Pěnčík[2], Přemysl Kršek[3], Alois Nečas[4]

[1]Department of Surgery and Orthopaedics, Clinic for Diseases of Dogs and Cats, Faculty of Veterinary Medicine, University of Veterinary and Pharmaceutical Sciences, Brno, Czech Republic
[2]Institute of Civil Buildings, Faculty of Civil Engineering, [3]Department of Computer Graphics, Faculty of Information Technology, Brno University of Technology, Brno, Czech Republic
[4]CEITEC VFU, University of Veterinary and Pharmaceutical Sciences Brno, Czech Republic

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Abstract

The study deals with the possibility of substituting time- and material-demanding mechanical testing of a bone defect fixation by mathematical modelling. Based on the mechanical model, a mathematical model of bone-implant construct stabilizing experimental segmental femoral bone defect (segmental ostectomy) in a miniature pig *ex vivo* model using 4.5 mm titanium LCP was created. It was subsequently computer-loaded by forces acting parallel to the long axis of the construct. By the effect of the acting forces the displacement vector sum of individual construct points occurred. The greatest displacement was noted in the end segments of the bone in close proximity to ostectomy and in the area of the empty central plate hole (without screw) at the level of the segmental bone defect. By studying the equivalent von Mises stress σ_{EQV} on LCP as part of the tested construct we found that the greatest changes of stress occur in the place of the empty central plate hole. The distribution of this strain was relatively symmetrical along both sides of the hole. The exceeding of the yield stress value and irreversible plastic deformations in this segment of LCP occurred at the acting of the force of 360 N. These findings are in line with the character of damage of the same construct loaded during its mechanic testing. We succeeded in creating a mathematical model of the bone-implant construct which may be further used for computer modelling of real loading of similar constructs chosen for fixation of bone defects in both experimental and clinical practice.

Fracture fixation, implant failure, material deformation, yield stress, displacement vector sum

In our previous studies we investigated the mechanical properties of the “Locking Compression Plate” (LCP) (Synthes® Swiss) used for stabilization of bone lesions after transplantation of mesenchymal stem cells (MSCs) in miniature pigs (Nečas et al. 2010b; Nečas et al. 2010c; Urbanová et al. 2010). We found that the five-hole titanium 4.5 mm LCP appears to be a more suitable implant than the six-hole 3.5 mm LCP for buttress osteosynthesis of a large segmental femoral defect (Nečas et al. 2010a). In the case of the 4.5 mm LCP, the implant failure was noted only sporadically. It is possible to eliminate these failures by improving the mechanical properties using the “plate and rod” technique (Hulse et al. 1997).

Our previous mechanical testing (Urbanová et al. 2010) was very demanding in terms of time and material. Another flaw of mechanical testing turned out to be the limited possibility of setting the acting change in the direction of acting force which would require creating new bone force. Each sample with the defect stabilized by LCP required producing new clumping equipment. Therefore, we attempted to transfer the whole problem to the level of computer modelling.

The aim of the study was to create a mathematical model of the bone-implant construct (BIC) which would correspond with its defined properties to a real construct used for

Address for correspondence:
MVDr. Lucie Urbanová
Department of Surgery and Orthopaedics
Small Animal Clinic, Faculty of Veterinary Medicine
University of Veterinary and Pharmaceutical Sciences Brno
Palackého tř.1/3, 612 42 Brno, Czech Republic

Phone: +420 541 562 349
Fax: +420 541 562 344
E-mail: lucieurbanova@email.cz
http://actavet.vfu.cz/

mechanical testing, and to compare the results of mathematical modelling with the results of previous mechanical tests.

Materials and Methods

The model for the mathematical modelling at the Brno University of Technology were the same *ex vivo* samples for testing the mechanical properties of flexible bridging osteosynthesis of the segmental diaphyseal defect of the femur with 4.5 mm LCP and four locking screws in miniature pigs (Urbanová et al. 2010) that were used in a mesenchymal stem cells (MSCs) transplantation study (research project NPV II 2B06130). Three-dimensional reformats of the bone-implant construct were created using computed tomography at the Department of Diagnostic Imaging SAC of the Faculty of Veterinary Medicine, UVPS Brno. For definition of the mathematical bone model, geometry data from CT scans were used in the form of raster volume data, digital images formed by a matrix of points (Španěl et al. 2007). After segmentation, vectorization and smoothing of tissues, 3D geometric vector model was imported into Rhinoceros 3D CAD system (http://www.cz.rhino3d.com). In this system, a closed solid 3D geometric bone model was created using NURBS surfaces (http://www.rhino3d.com/nurbs.htm), including the internal anatomical structures of the femur. The model was supplemented with an implant, titanium five-hole 4.5 mm LCP and four locking screws (with central plate hole left empty without screw), including polymethacrylate blocks (PMMA) allowing its clamping to the testing machine (Urbanová et al. 2010). The solid 3D geometric model was imported using the SAT format to the ANSYS (http://www.ansys.com/) analysis system for analysis using the finite element method.

With regard to the complicated geometry of the analyzed bone-implant construct (femur-LCP-screws-PMMA), during the discretization of the problem, i.e., creating a finite elements mesh (ANSYS 2010), to all parts of the analysis model except for the bone fixing system quadratic 3D finite elements of type SOLID186 [ELEM] were applied in the shape of a hexahedron, and their reduced forms (i.e. femur, screws, PMMA) and SOLID187 [ELEM] in the shape of a pyramid (i.e. titanium five-hole 4.5 mm LCP). For the bone fixing system, linear 3D finite elements of type SOLID185 [ELEM] were used. When creating a finite element mesh, the mapped meshing method (i.e. implant system) was used in volumes with simple geometry; for general volumes, the free meshing method was used.

During the behaviour analysis of the implant system consisting of titanium five-hole 4.5 mm LCP and screws, loaded by forces acting parallel to the long axis of the BIC system, deformations were taken into account when the equilibrium conditions were formed on a deformed structure. The nonlinear material behaviour of the bone-implant construct was taken into account when irreversible plastic deformations of the material occur upon reaching the yield stress value. Description of nonlinear material behaviour was carried out using a suitable material model, i.e. the yield criteria, the plastic flow rule and the hardening criteria. The behaviour of screws (Ti-6Al-7Nb) and LCP (CP-Ti grade 4) was modelled using a bilinear isotropic hardening material model BISO which uses the von Mises yield criteria coupled with an isotropic work hardening assumption (Kohnke 2010). For description of the material model BISO, material properties were used that are listed in Table 1, where E is the modulus of elasticity, EH is the hardening modulus, μ is the Poisson's ratio and σy is the yield stress. Material behaviour of other parts of the analysis model were described using the isotropic material model ISO, in which only reversible elastic strains arise and which was described by the modulus of elasticity E and the Poisson's ratio μ (Table 1).

Boundary conditions of the analysis model were designed on the analysed BIC in order to model the boundary conditions as for the real load test. At the bottom of the PMMA blocks allowing its clamping to the testing machine (Urbanová et al. 2010) a cylindrical boundary condition allowing free rotation around the axis of the circular arc was considered. The boundary condition on the top of the fixing system was defined in order to allow only vertical displacement, i.e. displacement in the direction of S-I femur.

Regarding the type of analysis (large deflection analysis combined with a materially nonlinear analysis), when the solution was carried out in an iterative process, the analysis model was loaded by an incremental load acting

Table 1. Material characteristics of the material models used.

Material*	Model	E (MPa)	E_H (MPa)	σ_y (MPa)	μ (-)
Bone mounting system - steel S235	ISO	210000	-	-	0.3
Polymethacrylate blocks - PMMA	ISO	3000	-	-	0.4
Cortical tissue	ISO	15230	-	-	0.3
Spongious tissue	ISO	225	-	-	0.3
Screws (Ti-6Al-7Nb) - BISO	BISO	112500	5625 (E/20)	800	0.35
LCP (Ti grade 4)	BISO	105000	5250 (E/20)	480	0.37

*material characteristics are taken from the producer of LCP (www.synthes.com) and from MathWeb (www.matweb.com) in the direction of S-I femur (parallel to the long axis of the analysed structure). The load applied in one increment (i.e. load step) was 30 N. A total of 40 increments were applied, at which an equilibrium state was found.

The output of the analysed solution of the BIC (femur-LCP-screws-PMMA) performed by ANSYS analysis system was generally the nodal displacement vector {u}, from which the strain vector {ε} and stress vector {σ} were determined (Kohnke 2010). In the evaluation of the mathematical modelling, the nodal displacement vector {u} in all global axis directions (UX, UY and UZ), as well as the displacement vector sum (USUM), were monitored. Fig. 1 (Plate xy), shows the displacement vector sum USUM of the analysed system under the load of 1.05 kN and a graph presenting the dependency of the vertical displacement of the top part of the bone fixing system and the displacement of point A in place of free hole of the LCP in direction of global axis on the size of the applied load.

Verification of stresses in different parts of the BIC system was performed using the equivalent von Mises stress σ_{EQV} according to the relation using principal stresses σ1, σ2 and σ3 (Kohnke 2010)

$$\sigma_{EQV} = \left(\frac{1}{2}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]\right)^{\frac{1}{2}}$$

or using components of the stress vector {σ}

$$\sigma_{EQV} = \left(\frac{1}{2}\left[(\sigma_X - \sigma_Y)^2 + (\sigma_Y - \sigma_Z)^2 + (\sigma_Z - \sigma_X)^2 + 6\,(\sigma^2_{XY} + \sigma^2_{YZ} + \sigma^2_{XZ})\right]\right)^{\frac{1}{2}}$$

The process of gradual development of plastic parts in the LCP was monitored beside the equivalent von Mises stress σ_{EQV} also by the equivalent von Mises plastic strain ε_{pl}. Using mathematical modelling, a detailed study was created of the equivalent von Mises stress σ_{EQV} distribution in the LCP as a part of tested BIC system. Using this mathematical modelling, places were also determined where stresses exceeded the yield stress, i.e. places where irreversible plastic strains of the material occurred.

Results

From the displacement vector sum of individual points of the structure at the loading of the bone-implant construct (Plate I, Fig. 1) it is apparent that the greatest effect of the acting forces of load in the direction S-I on the mathematical bone-implant model occurs in those bone segments that are in close proximity of the ostectomy defect, and in that part of the implant that bridges the femoral ostectomy (in the place of the central unfilled screw-hole of the LCP).

Distribution of the equivalent von Mises stress σ_{EQV} (Plate I, Fig. 2) on the LCP as part of the tested model of bone-implant construct showed that the biggest changes in stress occurred in the place of the central unfilled screw-hole of the LCP, and the distribution was relatively symmetrical along both sides of the hole. Irreversible plastic strains or the exceeding of the yield stress on the LCP occurred in the mentioned area of LCP at the acting of 12 load increments; i.e. at the acting of a force of the 360 N magnitude. Fig. 2 shows the gradual development of plastic parts in the LCP when considering a colour range at the interval of 0 to 480 MPa which corresponds to the yield stress σ_y. Those areas of the LCP implant model where the yield stress value was exceeded (i.e., places with irreversible plastic strains) are marked using grey colour (Fig. 2).

Discussion

Performing mechanical tests of different methods of fracture fixation before their introduction into clinical practice plays an important role in the development of new materials and operation procedures. By means of these tests it is possible to verify the adequate solidity and resilience of the chosen fixation apparatus against predefined forces. A disadvantage of such testing is the demand on time and material. For each mechanical test, new fixation equipment is needed (plates, screws, nails, etc.) but also a new bone sample on which the implant is applied. Every change in the setting of the acting force (bending, pressure, rotation, etc.) must be tested in several samples for the result to be considered valid. We assume that all these limitations may be solved by substituting mechanical tests by mathematical modelling. Although the analysis of the results of the force acting on such a complex structure as the bone with a defect fixated using a LCP implant is also relatively time-demanding, it does not require the presence of human personnel and after the initial input of appropriate parameters, a new sample for further testing is no longer needed. One big advantage of mathematical modelling may also be seen in more freedom when setting the acting forces. Moreover, a mechanical testing device is limited by the given setting of direction and magnitude of the acting force, and changing this setting usually requires the production of a new additional feature that would allow the clumping of the sample into the mechanical testing device (Urbanová et al. 2010). During mechanical testing, it is also very demanding to combine the acting of more forces at once which certainly happens *in vivo*. The setting of properties of acting forces in mathematical computing is much simpler compared to mechanical testing. Considering the fact that a precise description of forces acting on the pig femur in this bone-implant construct has not yet been given in literature, the loading of BIC by forces acting parallel with the long axis of the bone was used as first. In our findings, failure of the bone-implant construct may be expected when the critical stress value is exceeded in those bone segments that are in close proximity to the ostectomy defect and in that part of the implant that bridges the femoral ostectomy (in the place of the unfilled central screw-hole of the LCP). The distribution of the equivalent von Mises stress σ_{EQV} (Plate I, Fig. 2) in the LCP (as part of the tested model of bone-implant construct) has shown that the biggest changes in stress occur in the place of the unfilled central screw-hole of the LCP, and the distribution of this stress is relatively symmetrical along both sides of the hole. Irreversible plastic strains, or the exceeding of the yield stress, occurred in the mentioned area of LCP at the acting of a force of 360 N (12 load increments at the interval of 0 to 480 MPa) which corresponds to the value of yield stress (the parts of the model of LCP implant marked in grey in Fig. 2).

The acting stress and the resulting strains of the bone-implant construct in this mathematical model represented by the colour range corresponded with the changes in stress and strains of BIC during previous mechanical tests which verified the appropriateness and suitability of parameters input during the creation of this mathematical model of BIC (Urbanová et al. 2010). Based on these findings we may state that a suitable mathematical model of the bone-implant construct has been created which may be further used for mathematical modelling of the loading of similar structures used both in clinical practice and in experiment, by forces of different magnitudes and acting in a complex way in different directions, in order to be able to computer model as accurately as possible the real acting of forces upon implants used for bone defect fixation *in vivo*.

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