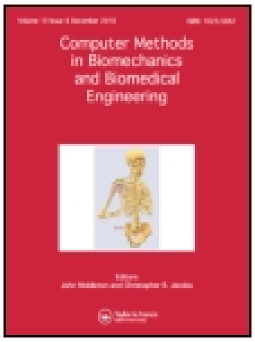

Computer Methods in Biomechanics and Biomedical Engineering

ISSN: 1025-5842 (Print) 1476-8259 (Online) Journal homepage: https://www.tandfonline.com/loi/gcmb20

Bone remodelling analysis of a bovine femur for a veterinary implant design

L.B. Rodrigues , D.S. Lopes , J. Folgado , P.R. Fernandes , E.B. Pires , E.B. Las Casas & R.R. Faleiros

To cite this article: L.B. Rodrigues , D.S. Lopes , J. Folgado , P.R. Fernandes , E.B. Pires , E.B. Las Casas & R.R. Faleiros (2009) Bone remodelling analysis of a bovine femur for a veterinary implant design, Computer Methods in Biomechanics and Biomedical Engineering, 12:6, 683-690, DOI: 10.1080/10255840902865641

To link to this article: https://doi.org/10.1080/10255840902865641

Published online: 09 Apr 2009.

Computer Methods in Biomechanics and Biomedical Engineering
Vol. 12, No. 6, December 2009, 683–690

Bone remodelling analysis of a bovine femur for a veterinary implant design

L.B. Rodrigues[a1], D.S. Lopes[b2], J. Folgado[b3], P.R. Fernandes[b]*, E.B. Pires[c4], E.B. Las Casas[d5] and R.R. Faleiros[e,6]

[a]*State University of Bahia Southwest, Campus of Itapetinga, Pça Primavera, 40, 45700-000 Itapetinga, Bahia, Brazil;* [b]*IDMEC/IST, Technical University of Lisbon, Av. Rovisco Pais, 1049-001 Lisbon, Portugal;* [c]*ICIST/IST, Technical University of Lisbon, Av. Rovisco Pais, 1049-001 Lisbon, Portugal;* [d]*DEES/EE, Federal University of Minas Gerais, Av. do Contorno, 842, 2° andar, 3110-002 Belo Horizonte, MG, Brazil;* [e]*DCCV/EV, Federal University of Minas Gerais, Av. Antônio Carlos, 6627, Pampulha, 30161-970 Belo Horizonte, MG, Brazil*

(*Received 22 January 2009; final version received 3 March 2009*)

Dedicated to our colleague and friend J.A.C. Martins

The response of bovine bone to the presence of an implant is analysed with the aim of simulating bone remodelling in a developing model of a polymeric intramedullary interlocking nail for veterinary use. A 3-D finite element model of the femur diaphysis is built based on computed tomography images and using a CAD-based modelling pipeline. The bone remodelling process after the surgery is analysed and compared with the healthy bone. The remodelling law assumes that bone adapts to the mechanical environment. For the analyses a consistent set of loads is determined for the bovine walk cycle. The remodelling results reproduce the morphologic features of bone and provide evidence of the difference on the bone behaviour when comparing metallic and polymeric nails. Our findings indicate that an intramedullary polymeric nail has the advantage over the metallic one of improving long-term bone healing and possibly avoiding the need of the implant removal.

Keywords: bone remodelling; intramedullary nail; veterinary; bovine femur; fracture healing; finite elements

Introduction

The treatment of fractures of long bones is still a challenge for veterinary medicine. In fact, long bone fractures in large animals often represent a bad prognosis, since limb immobilisation may prevent the standing position or the use of the affected limb and the permanence in recumbency or the overload of the contralateral limb for long periods can cause irreversible injuries due to heavy weight (McClure et al. 1998). A solution is the use of internal fixation devices for fracture healing without the need of additional immobilisation techniques and allowing early use of the affected limb. However, the available products that are used in surgery to fix bone fragments are too expensive and are adapted from human devices (Aithal et al. 2004). For these reasons, there is a clinical demand for developing implants specifically designed to be used in large animals. The most widely used implants are bone plates and intramedullar nails, which are inserted and/or fixed to bone tissue with screws. The intramedullary interlocking nail, which has been used in human orthopaedics since the 1950s (Aron et al. 1995), was introduced in the early 1990s in the treatment of fractures of long bones in small animals (e.g. cats and dogs, Dueland et al. 1999; Durall and Diaz-Bertrana 2005). Approximately in the same period, some studies on the use of intramedullary interlocking nails in fractures of long bones in large animals were performed (Watkins 1990; McDuffee et al. 2000).

The response of bovine bone in the presence of an implant is analysed with the aim of developing a polymeric interlocking nail, less expensive than a metallic one and not requiring a new surgery for its removal. This analysis is performed using a suitable computational bone-remodelling model (Fernandes et al. 1999). There are three major steps to achieve this objective:

(1) the construction of a 3-D finite element mesh of the diaphysis of a bovine femur, using a CAD-based geometric modelling pipeline that relies on computed tomography images (Lopes et al. 2008);
(2) the definition of a consistent set of mechanical loads to be applied on the bovine femur during the walk cycle, and
(3) the bone remodelling analysis using the computational model (Fernandes et al. 1999) to compare the performance of a polymeric nail with a conventional metallic implant.

Results are obtained for four different mechanical cases corresponding to the femur subjected to two loading

*Corresponding author. Email: prfernan@dem.ist.utl.pt

ISSN 1025-5842 print/ISSN 1476-8259 online

DOI: 10.1080/10255840902865641
http://www.informaworld.com

conditions both with and without the implant. The remodelling law is derived from the solution of an optimisation problem that includes the structural performance and the metabolic cost to maintain bone tissue. It is assumed that bone adapts to the mechanical environment so that the stiffest bone structure for the given applied loads is achieved. Material properties, loading and boundary conditions are provided to the model in order to perform the biomechanical analyses. The results show that the remodelling model reproduces the morphologic features of bone and provide clear evidence of the difference on the bone behaviour when comparing the remodelling processes using metallic and polymeric nails.

In conclusion, the study ranges from modelling the geometry of the bone structure up until the decision making of which polymeric material better suits the biomechanical environment. It should be noted that the use of computational simulations has been deeply supported by the scientific community, avoiding unnecessary animal pain and guaranteeing ethical regulations (Paixão and Schramm 1999). Furthermore, computational analyses have the advantage of time and cost reductions compared to *in vivo* experiments (Prendergast 1997).

Methods

Geometric and finite element model

In order to obtain the finite element model of the diaphysis of the bovine femur, a CAD-based modelling pipeline is developed (Lopes et al. 2008). The diagram of Figure 1 gives an overall view of the pipeline. The dark grey (upper) boxes contain the data file extension, the white (middle) boxes present the software tool name, and the grey (lower) boxes indicate the functionality of each software tool. The file formats correspond to: DICOM medical image (∗.dcm); Analyse medical image (∗.hdr/∗.img); CUBIT native journal file (∗.jou); ABAQUS® native input file (∗.inp).

Bone tissue in computed tomography images is segmented with 3D snakes (Yushkevich et al. 2006), each of which timely and spatially evolves according to a region competition algorithm. Such a segmentation method has been successfully implemented in ITK-SNAP. In order to obtain a continuous surface representation from the digital images, a point cloud is extracted from the resulting segmented data. Morphological image operators from the Image Processing Toolbox 6.2 – MATLAB® are used. Several spline curves are interpolated from the point cloud and the bone surfaces are then obtained by sweeping these curves. After closing the diaphysis's endings, a boundary representation (B-REP), also designated as solid model, of the femur diaphysis is generated. The solid model and the corresponding finite element meshes are obtained with CUBIT. A detailed description of the geometrical modelling process illustrated in Figure 1 can be found in Lopes et al. (2008). The resulting meshes are used in finite element analyses for bone remodelling studies, although other applications might be considered, such as, rapid prototyping and 3D visualisation (Sun et al. 2005).

A total of three geometric models (CAD entities and their corresponding meshes) are obtained to suit specific goals within the overall implant design project: A1, the diaphysis with both cortical tissue and bone marrow regions used to calibrate the parameters of the remodelling code; A2, the diaphysis only with cortical tissue in order

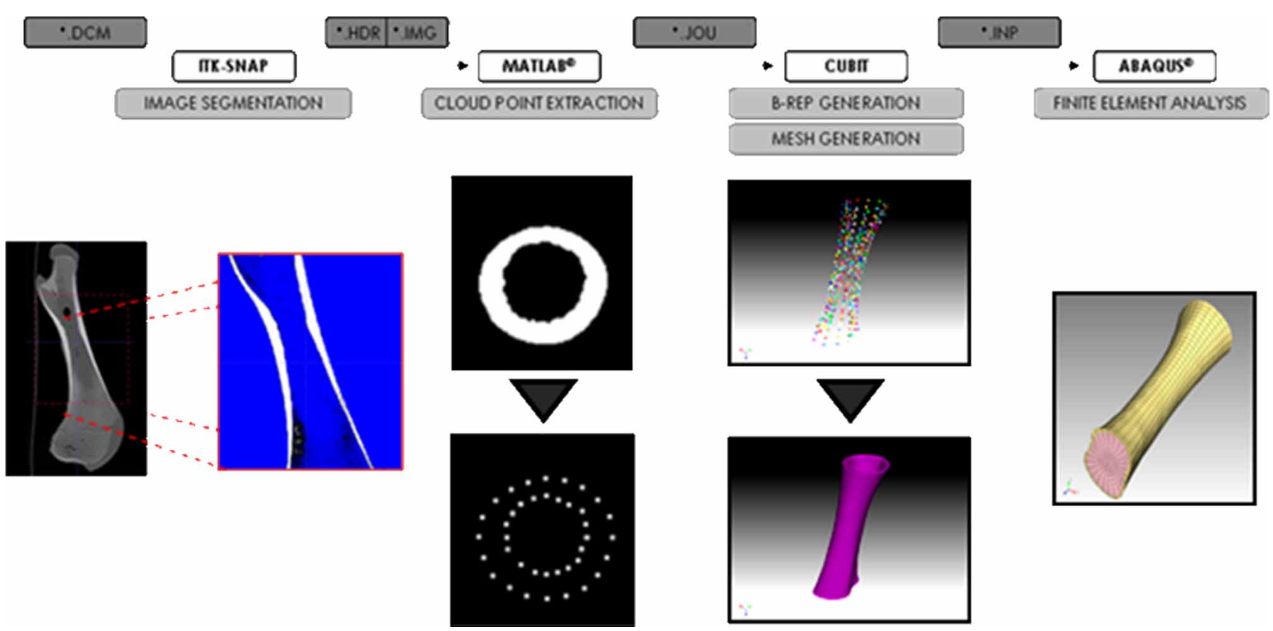

Figure 1. Diagram of the software pipeline used for the geometric modelling.

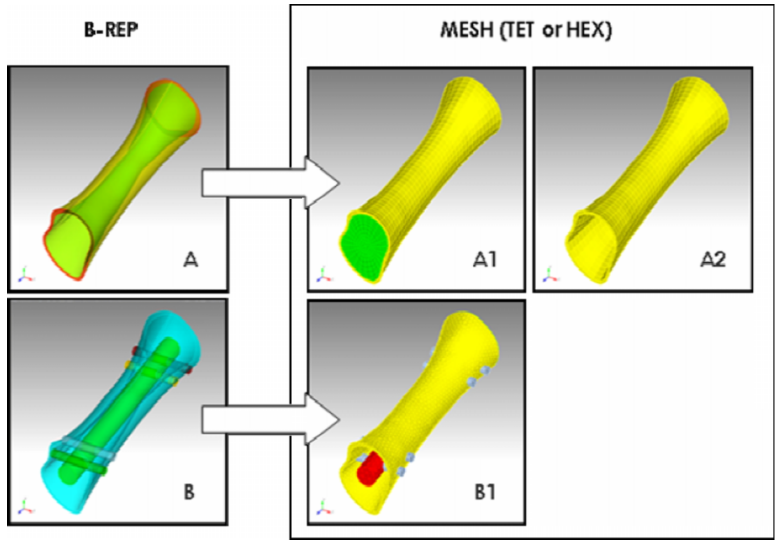

Figure 2. Solid and finite element models of the diaphysis of the bovine femur.

to verify the parameter values previously obtained and to observe the behaviour of a healthy bone; B1, the diaphysis with cortical tissue and intramedullary interlocking nail to study the implanted bone after the healing process. Hexahedral and tetrahedral meshes are generated according to the geometric features of the model. Figure 2 shows both the geometric and the finite element models: mesh A1 has 7920 hexahedral 8-node elements, mesh A2 has 9600 hexahedral 8-node elements and mesh B1 has 68,202 tetrahedral 4-node elements with 43,584 elements for the diaphysis region.

Loads

An important issue for the accuracy of the computational modelling of the biomechanics of the bovine bone is the loading condition. The lack of data in the literature motivated the acquisition of this information using motion analysis techniques.

A motion capture system registers the limb trajectory and a force platform acquires the ground reaction force of the calf's hoof as shown in Figure 3 (Rodrigues et al. 2007a). The loads acting on the proximal femoral extremity are then calculated assuming the leg as a multi-body system and by guarantying mechanical equilibrium at each instant of time. Since only the vertical load is registered, the longitudinal and transversal components are determined as a percentage of the vertical load (van der Tol et al. 2003).

Two different loading conditions are considered. The first one consists of five loads corresponding to five different instances of the calf gait cycle: heel strike, maximum braking, midstance, maximum propulsion and push-off. In the second one, an additional load is included corresponding to the calf in the standing static position (Rodrigues et al. 2007b). For the five loads simulation, equal percentage for each load (20%) is given. When the static load is considered, the weights are 50% for this load and 10% for each one of the remaining loads. It is assumed that the calf is grazing most of the time.

Each load case is represented by forces and moments acting on the proximal femoral extremity of the finite element model. Their values are shown in Table 1. The coordinate system is such that the z-axis is aligned with the axis of the femoral bone (proximal–distal direction) with the x-axis along the lateral–medial direction and the y-axis along the anterior–posterior direction.

Bone remodelling model

The bone remodelling model developed by Fernandes et al. (1999) is adopted in this work. In this model, the bone remodelling law is derived assuming that bone self-adapts in order to achieve the stiffest structure for the supported loads. It combines a stiffness criterion with the cost of bone formation that controls the total bone mass. Trabecular bone structure is modelled as an orthotropic porous material obtained by the periodic repetition of a cubic cell with a prismatic hole. The relative density, ρ, depends on the dimension of the local hole and evolves in order to satisfy the remodelling law given by:

$$\sum_{r=1}^{P}\left[\alpha^{r}\frac{\partial E_{ijkl}^{H}(\rho)}{\partial\rho}\varepsilon_{ij}(\mathbf{u}^{r})\varepsilon_{kl}(\mathbf{u}^{r})\right]-\kappa=0. \qquad (1)$$

The value of the relative density, ρ, ranges from 0 (absence of bone) to 1 (compact bone). Values in between correspond to spongy bone. Equation (1) is the bone

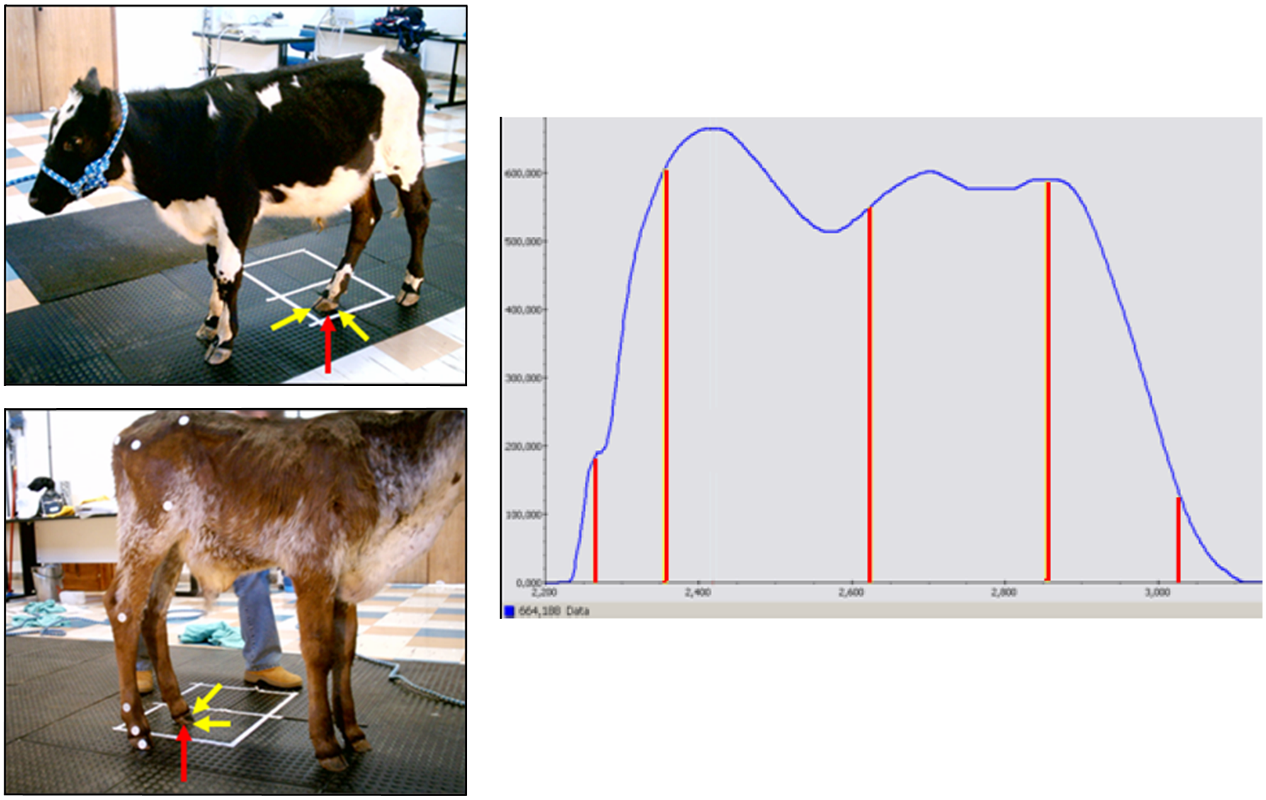

Figure 3. Load estimation. Acquisition of ground reaction force in the biomechanics lab (left) and the diagram of the ground reaction force during the gait cycle (right). The vertical lines represent the five instants considered in this work.

remodelling law, in the sense that whenever it is satisfied the remodelling equilibrium is achieved. In this equation, the mechanical stimulus is determined using a multiple load formulation where a weighted set of P loads characterises the loading environment applied to bone, α is the weight for each load, $\varepsilon_{ij}(\mathbf{u}^r)$ is the strain field for the load case r and E^H_{ijkl} are the bone elastic properties obtained by the homogenisation method (Guedes and Kikuchi 1990). In the remodelling law (1), the cost of bone formation is assumed constant and is expressed by the parameter κ. This parameter assumes an important role in the model since the resulting bone mass will depend strongly on its value. The assigned value for κ is problem dependent since κ varies with several biological factors such as age, hormonal status and disease of the individual. In the case of this work κ must be determined in order to reproduce the biological conditions of the calf.

Results

The bone remodelling model described above is applied to the bovine femur. To calibrate the model and find the numerical parameters, namely the cost of bone formation κ, the diaphysis of the femur with cortical bone and medullar

Table 1. Loads.

Load case	Load	x	y	z
0, Standing static position	Force (N)	0	70.82	154.09
	Moment (N mm)	-5.75×10^3	0	0
1, Heel strike	Force (N)	11.6	21.08	120.8
	Moment (N mm)	-11.58×10^3	9.15×10^3	-484.58
2, Maximum braking	Force (N)	21.44	44.67	398.3
	Moment (N mm)	13×10^3	16.31×10^3	-2.53×10^3
3, Midstance	Force (N)	5.73	106.16	324.11
	Moment (N mm)	-8.57×10^3	4.1×10^3	-1.13×10^3
4, Maximum propulsion	Force (N)	8.28	122.3	251.59
	Moment (N mm)	4.16×10^3	5.57×10^3	-2.84×10^3
5, Push-off	Force (N)	0	13.8	31.24
	Moment (N mm)	4.13×10^3	0	0

Table 2. Elastic properties.

Material	E (GPa)	ν
Bone	21.9	0.30
Stainless steel	210	0.35
Polypropylene	1–1.6	0.43
Polyacetal	2.55–3.5	0.41
Polyamide	1.4–2.8	0.40

canal (A1) is first considered. Then, these parameters are used in the finite element model that presents only cortical bone without (A2) and with an interlocking nail (B1). In the model with the nail, bone remodelling is analysed with implants made of different materials: stainless steel, polypropylene, polyacetal and polyamide.

All finite element models are fixed at the distal extremity and a rigid plate is placed on the upper extremity where loads are applied. The two different loading conditions defined above are considered. The bone material properties are computed by the homogenisation method (Guedes and Kikuchi, 1990) for the porous material considered in the remodelling model. For these computations, the base material is assumed as compact bone with Young modulus $E = 21.9$ GPa and Poisson ratio $\nu = 0.3$ (Cowin 1989). Bone properties as well as the properties of the materials used in the implants are summarised in Table 2 (Black and Hastings 1998).

For a given set of loads it is necessary to find the parameter κ that corresponds to the metabolic cost of bone formation of the bovine femur. To achieve this, different values of κ are tested in the computational model for the finite element mesh with the medullar cavity filled with elements. The results obtained for five loads are shown in Figure 4. In this figure, red corresponds to high bone densities (compact bone) and blue corresponds to low densities (absence of bone). Based on these bone density distributions, the value of $\kappa = 0.30 \times 10^{-2}$ is chosen. In fact, this value is the one that better reproduces the real bone as shown in Figure 5, where the comparison of the computational results with the real bone is presented. For a better comparison with the medical images, the colours assigned to the density in Figure 5 are changed so that white corresponds to compact bone and black corresponds to absence of bone.

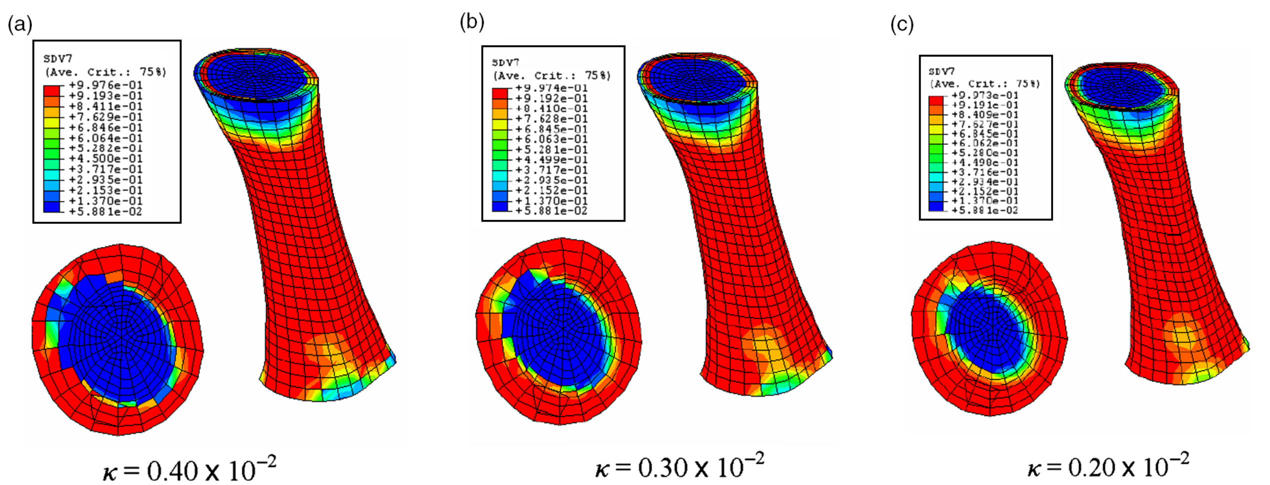

Figure 4. Bone remodelling study of the intact bone model with both cortical and medullar regions. Results for the biological parameter κ for five loads with the hexahedral mesh.

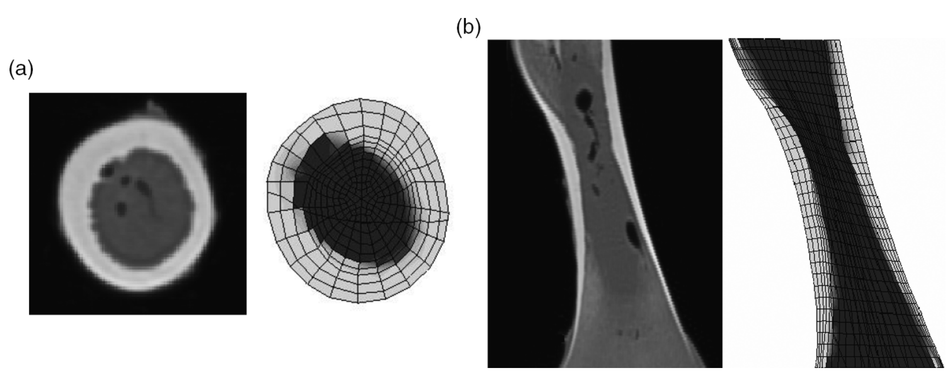

Figure 5. Comparison between the CT images of the real bovine bone and the modelling result. Transversal (a) and sagittal (b) sections.

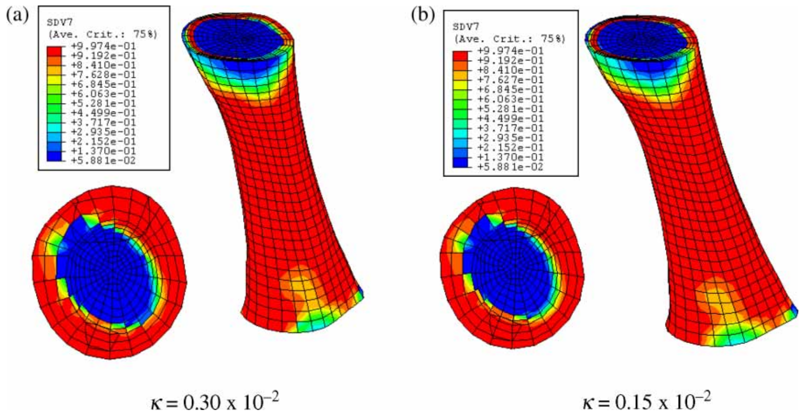

Figure 6. Bone remodelling study of the intact bone model with both cortical and medullar regions. Results for the cases with five (a) and six (b) loads with the hexahedral mesh.

Figure 6 shows the results of bone remodelling for five and six loads. It should be noted that a different load set implies a different biologic parameter κ (Fernandes et al. 1999). In both examples, the results reproduce the geometric characteristics of bone, since the medullar cavity is clearly identified, and the region of compact bone is well defined following the real bone geometry.

For verification purposes, the remodelling model is applied to the external layer of the femur, corresponding to the cortical bone (finite element mesh A2). In this case the parameter κ is assumed equal to 0.3×10^{-2} and 0.15×10^{-2} for the cases with five and six loads, respectively. The results obtained are presented in Figure 7. The domain is filled with full material (compact bone)

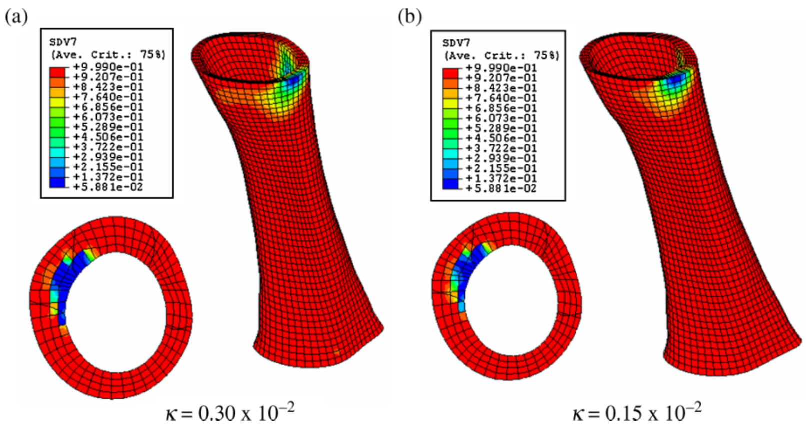

Figure 7. Bone remodelling results for the model with only the cortical layer: (a) five loads and (b) six loads.

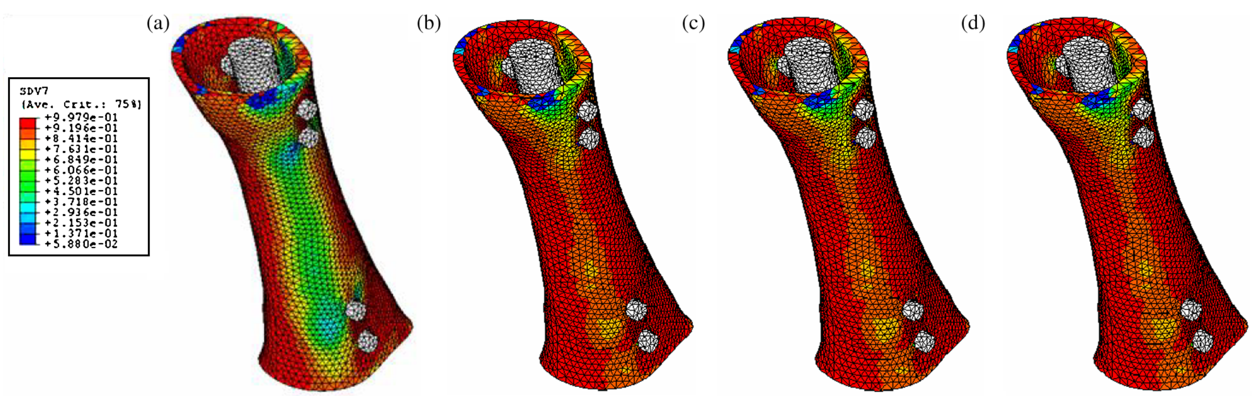

Figure 8. Bone remodelling results for the case with five loads and (a) metallic and polymeric nail, (b) polypropylene, (c) polyacetal and (d) polyamide.

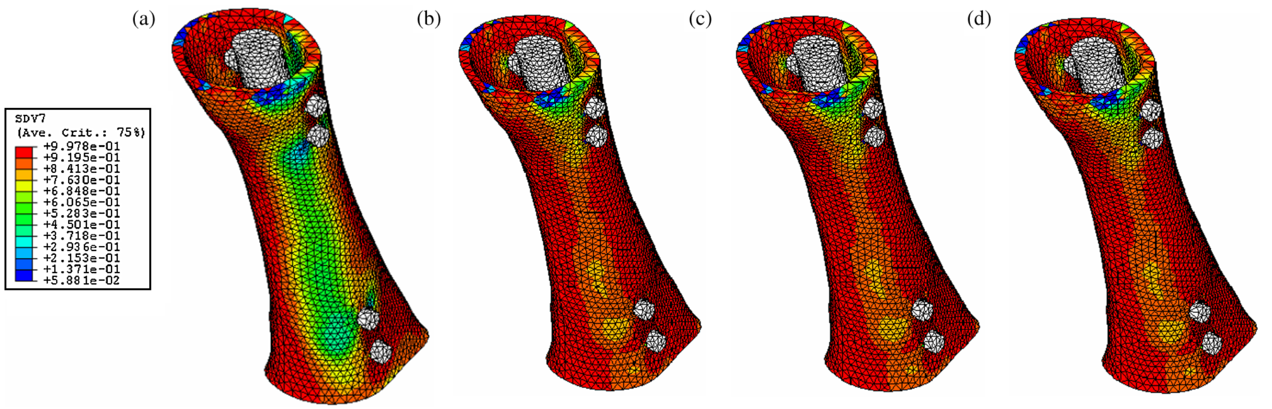

Figure 9. Bone remodelling results for the case with six loads and (a) metallic and polymeric nail, (b) polypropylene, (c) polyacetal and (d) polyamide.

except in the upper extremity, probably due to boundary conditions. This means that the adopted values for κ are also suitable for the hollow model.

After calibration, the model is used in the case of the implanted bone. The geometry represents a treated bovine femur with the intramedullary nail after the bone healing. Both metallic and non-metallic implants are tested. Figures 8 and 9 show the results for the different implant materials. The stiffest implant, i.e. the metallic one, presents more bone resorption than the polymeric implants. This leads to the conclusion that a polymeric implant should be used if the option is to have a permanent implant.

Conclusions

In this work, bone remodelling analyses are performed to study the behaviour of the femur of a bovine with an intramedullary implant. To achieve this, a geometric modelling pipeline that generates, in a semi-automatic manner, B-REPs and high quality volumetric meshes of long bone diaphysis from medical images is developed. Such meshes can be used for finite element analyses, rapid prototyping and 3D visualisation. The obtained meshes are used here to perform a bone remodelling study using a remodelling law derived from a topology optimisation problem. The results show that the bone remodelling model reproduces the observed behaviour of bovine bone, with maximum values of bone density in the region corresponding to the cortical tissue and zero values in the region corresponding to bone marrow. The results for the model of bone with implant show that the use of polymeric nails yields a better long-term behaviour (with respect to bone remodelling), with no difference between the polymeric materials. The difference is made clear when comparing the remodelling results using metallic and polymeric nails; however, the decision on the best polymeric nail to use still requires an analysis of the stresses in the models in order to compare their maximum values for each load case with the strength of the materials used in the implants. Our findings indicate that the use of an intramedullary polymeric nail for bovine femur repair has the advantage over the metallic one of improving long-term bone healing and possibly avoiding the need of a second surgical procedure for implant removal.

Acknowledgements

The authors gratefully acknowledge the Fundação para a Ciência e a Tecnologia (FCT) for the support granted in the context of POCI 2010, of Project Plurianual Base POCTI-SFA-9-76, of Project PTDC/EME-PME/71436/2006 and of PhD grant SFRH/BD/45319/2008. The authors also acknowledge the support granted in the context of Project Capes/Grices 148/06 from FCT and from Coordenação de Aperfeiçoamento de Pessoal de Nível Superior and grants CVZ 836/06 and EDT-506/07 from Fundação de Amparo à Pesquisa do Estado de Minas Gerais.

Notes

1. Email: lucianobr@uesb.br
2. Email: danlopes@dem.ist.utl.pt
3. Email: jfolgado@dem.ist.utl.pt
4. Email: bpires@civil.ist.utl.pt
5. Email: estevam@dees.ufmg.br
6. Email: faleiros@ufmg.br

References

Aithal HP, Singh GR, Hoque M, Maiti SK, Kinjavdekar P, Amarpal, Pawde AM, Setia HC. 2004. The use of a circular external skeletal fixation device for the management of long bone osteotomies in large ruminants: an experimental study. J Vet Med A. 51:284–293.

Aron DN, Palmer RH, Johnson AL. 1995. Biologic strategies and a balanced concept for repair of highly comminuted long bone fractures. Vet Comp Orthop Traumatol. 7:35–38.

Black J, Hastings G. 1998. Handbook of biomaterial properties. Boca Raton (FL): Chapman & Hall.

Cowin SC. 1989. The mechanical properties of cortical bone tissue. In: Cowin SC, editor. Bone mechanics. Boca Raton (FL): CRC Press. p. 97–127.

Dueland RT, Johnson KA, Roe SC, Engen MH, Lesser AS. 1999. Interlocking nail treatment of diaphyseal long-bone fractures in dogs. J Am Vet Med Assoc. 214(1):59–66.

Durall, I, Diaz-Bertrana, MC. 2005. Fracture fixation using interlocking nails. Proceedings of the 30th World Small Animal Veterinary Association World Congress, Mexico City, Mexico.

Fernandes P, Rodrigues H, Jacobs C. 1999. A model of bone adaptation using a global optimization criterion based on the trajectorial theory of Wolff. Comput Methods Biomech Biomed Engin. 2:125–138.

Guedes JM, Kikuchi N. 1990. Preprocessing and postprocessing for materials based on the homogenenisation method with adaptive finite element methods. Comput Methods Appl Mech Eng. 83:143–198.

Lopes DS, Martins JAC, Pires EB, Rodrigues LB, Las Casas EB, Faleiros RR. 2008. A geometric modelling pipeline for bone structures based on computed tomography data: a veterinary study. In: Tavares JMRS, Natal Jorge RM, editors. Computational vision and medical image processing. Porto (Portugal): Taylor & Francis. p. 217–222.

McClure SR, Watkins JP, Ashman RB. 1998. *In vitro* evaluation of intramedullary interlocking nail fixation of transverse femoral osteotomies in foals. Vet Surg. 27:29–36.

McDuffee LA, Stover SM, Bach JM, Taylor KT. 2000. An *in vitro* biomechanical investigation of an equine interlocking nail. Vet Surg. 29:38–47.

Paixão RL, Schramm FR. 1999. Ethics and animal experimentation: what is debated? Cad Saúde Pública. 15(Suppl. 1): 99–110.

Prendergast PJ. 1997. Finite element models in tissue mechanics and orthopaedic implant design. Clin Biomech. 12(6): 343–366.

Rodrigues, LB, Las Casas, EB, Faleiros, RR, Menzel, H-J, Bretas, MS, Andrade, AGP. 2007a. Measurement of ground reaction forces on limbs of calves in a standing static position. Proceedings of the 19th International Congress of Mechanical Engineering, Brasilia, DF, Brazil.

Rodrigues, LB, Las Casas, EB, Faleiros, RR, Menzel, H-J, Bretas, MS, Andrade, AGP, Perilo, BS. 2007b. A preliminary evaluation of ground reaction forces on large animals hind limbs during gait. Proceedings of the 19th Brazilian Congress of Mechanical Engineering, Brasilia, DF, Brazil.

Sun W, Starly B, Nam J, Darling A. 2005. Bio-CAD modeling and its applications in computer-aided tissue engineering. Comput Aided Des. 37(11):1097–1114.

van der Tol PPJ, Metz JHM, Noordhuizen-Stassen EN, Back W, Braam CR, Weijs WA. 2003. The vertical ground reaction force and the pressure distribution on the claws of dairy cows while walking on a flat substrate. J Dairy Sci. 86:2875–2883.

Watkins JP. 1990. Intramedullary interlocking nail fixation in foals. Vet Surg. 19:80.

Yushkevich PA, Piven J, Hazlett HC, Smith RG, Ho S, Gee JC, Gerig G. 2006. User-guided 3D active contour segmentation of anatomical structures: significantly improved efficiency and reliability. Neuroimage. 31(3):1116–1128.