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What can finite element analysis tell us?

In this issue, O'Hare *et al*. describe the use of finite element (FE) analysis (FEA) in assessing the equine proximal phalanx (P1) [1], while Ramsay *et al*. used the same methodology to examine biomechanics of the equine hoof [2]. Finite element analysis is a new tool that may be unfamiliar to *Equine Veterinary Journal*'s readers. A search in SCOPUS with the keywords 'Finite Element Analysis' or 'Finite Element Method' gives 270,734 resulting articles (8 January 2013). Only 46 of these were categorised for 'Veterinary Sciences'. So what is this analysis method and can it be useful in veterinary medicine?

Clinical movement analysis and modelling of the musculoskeletal dynamics have become standard methods for estimating joint torques, muscle forces and intersegmental loads during movement. The models that are usually used in musculoskeletal modelling are so-called 'rigid body models' which indicates that the bones connected and articulated at the joints are modelled as infinitely rigid structures. If we want to have a closer look at the effects of the loading situation on bone – Which stresses and strains does the loading situation cause? How does it deform? What is the region with the highest risk of failure? – we have to go one scale deeper and look at bone tissue and its mechanical behaviour. Bones can be described as deformable solids, whose behaviour can be modelled using the theory of solid mechanics, and a numerical method called the FE method.

Young's modulus is used in mechanical engineering to describe the elasticity (stiffness) of homogeneous material samples. The linear range of the stress–strain curve is defined by the Hook's law (or the spring equation). Most materials (devices, machines and living tissues) are nonhomogeneous. Finite element analysis or the FE method is the attempt to cut the entire structure into homogeneous samples with a linear stress–strain relation and study their collective (group) behaviour in loaded situations. The interaction as compression of a material in the vertical axis (direction) leads to an expansion in both perpendicular transversal directions. The Poisson's ratio quantifies this phenomenon, which is called the Poisson effect. The results of FEA are the deformation, pressures and tensions for each FE of the investigated structure.

The behaviour of bone in a loaded condition is complex and difficult to predict. Bone is a highly nonhomogenous material, structured in a hierarchical way covering many length scales. Bone is anisotropic; the inclination of the stress–strain curve depends on the loading direction. Finite element analysis aims at understanding the relationship between bone structure and its mechanical function at specific hierarchical levels.

To set up an FE model we need data on geometry and material properties (Young's modulus and Poisson's ratio). Currently available imaging methods such as high-resolution quantitative computed tomography or high-resolution magnetic resonance imaging provide an assessment of bone architecture on a microscale with resolutions down to 40 μm *in vivo*, even lower on samples *in vitro*, and accurately reconstruct bone geometries including the complex shapes of the tiny trabeculae. Information on bone minerals can be derived from computed tomography images, allowing estimation of material properties (Young's modulus). Nanoindentation can be used to determine material properties of small bone samples experimentally. Standard mechanical testing such as compression tests can also be done on small bone samples on a microscale.

Once geometry and material properties have been defined, 'meshing' has to be done. Geometry is subdivided into a finite, large number of geometrically simple domains (elements) connected at their vertices (nodes). The single elements are mostly homogenous and isotropic; for more detailed analysis, nonhomogeneous (Young's modulus varying over the elements volume) elements can also be used and methods have been developed to consider bone's anisotropy [3]. In principle, every detail of the structure can be taken into account by using sufficiently small elements. In practice this may not be feasible due to the limitations of computer capacity.

Software packages are available to perform meshing of defined geometries automatically. For analyses on a microscale, the voxels from imaging are directly transferred into elements, usually ending up in millions of elements. Once a model is established, FEA is possible. External loads are applied to the bone structure; the FEA calculates nodal displacements and the resulting strains and stresses. With a nonlinear FEA plastic deformations can also be simulated if necessary – again at a much higher computing cost.

How bones respond to mechanical loading is fundamental to understanding fractures. Loads that are applied to bone during movement can be derived from classical movement analysis and biomechanical simulation. Applying FEA gives information on the regions with highest stress and can predict the areas of potential failure. Yosibash *et al*. [4] applied high-order FEA with nonhomogeneous orthotropic material properties to predict the yield of the proximal femur bone and validated their results experimentally.

Bone structure is highly optimised for its typical loading situation during movement. Any alterations of the external loading situation due to deformation, implants or stabilising devices change the stress distribution in the bone tissue and may consequently increase the risk of failure. Finite element analysis can be used to identify the regions of highest stress in bone at a specific loading situation. When the aim of the FEA is to conduct a failure analysis, a failure criterion must be defined that can be used to define the external conditions under which the bone fails. The risk of fracture is computed as a safety margin over the strain limit, assuming that the bone fails as a fragile material under tension or as a ductile material under compression. Designs of fixation devices (pins, screws, plates) or implants can be optimised using FE models. Lauer *et al*. [5] used FEA to determine the optimal mechanical properties of articulations and diagonals in an external skeletal fixator used in small animals. Computational methods have the advantage that it is more easy to look at greater numbers of variations than is practical in clinical and laboratory testing.

The advantages of FEA become even more obvious when it comes to issues where the loading situation can easily be modified as is the case with the hoof, for example. The benefit of manipulating heel heights remains controversial and FEA can be applied to quantify changes in loading on the hoof itself and adjacent structures. Finite element analysis has also been used in the risk assessment and prevention of age- and disease-related changes [6] and can be applied to monitor the effectiveness of drugs on the skeletal system.

In general, FE-based methods are often associated with huge effort, complexity and extensive computing costs. This is particularly true for studies of microstructure where nano- and microscale experimental methods are necessary and models with millions of nodes are handled. However, not all models need to be that extensive. For more clinical analyses such as the change of stress distribution in a bone due to a fixation pin, less complex models can be sufficient. The advantage of current research on the microscale is that more parameters on material properties and behaviour of bone tissue are being documented and are available for modelling and analyses on a larger scale. Additionally, new software packages are of great help during the modelling and simulation process, making FEA more easily accessible. Using microstructural FE models generated directly from computer reconstructions of trabecular bone it is now possible to perform a 'virtual experiment', i.e. to simulate a mechanical test in great detail and with high precision.

The first study using FE models in veterinary science was published by Bartel *et al*. [7] to optimise and reduce stress in a canine hip prosthesis. The stresses were determined using the stress–strain relationship of the materials and the FEA. The development of the personal computer and the progress in technology have made this CPU-intensive methodology easily accessible in the last decade. This is shown by the fact that 42 of 46 papers in veterinary science were published since 2000. A hoof model is a typical example of how FEA can be used to study a complex structure, consisting of nonhomogeneous materials [2]. That model predicted that raising the palmar angle increases the load on the dorsal laminar junction. Measurements are not always practicable and FEA offers an alternative approach to the problem, based on biomechanical estimations with the goal of providing the veterinarian with evidence on which to base decisions regarding appropriate therapy. Computer models are, of course, limited by the assumption on which they are based, and Ramsay *et al*.'s model [2] provoked some debate within the podiatary community [8–11].

O'Hare *et al*. [1] bring light into the darkness and present an FEA study of stress in the equine P1. Their model can be interpreted as a further development of diagnostic imaging. The first step of the method is usual medical imaging, via computed tomography microscans, the surface geometry and internal structures of the equine P1 was captured. The 3D surface was converted to a 3D volume mesh consisting of over 6 million linear tetrahedral elements, representing 3 components: cortical bone, trabecular bone and a fixation platform. Material properties (Young's modulus and Poisson's ratio) were assigned to each of the 3 model components based on previous studies and stress analysis via FEA was performed. With the restriction of this method, the impressive results show the increase of stress with the dynamics of gait in different areas of the P1.

By considering the results of FEA (estimated the stresses, strains and deformations of the special structure [P1]) veterinarians will have a deeper insight into the biomechanical behaviour of the materials (bones, tissues). Through this newly available technology, orthopaedic surgeons can gain a better understanding of the biomechanics and therefore of therapies in future.

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