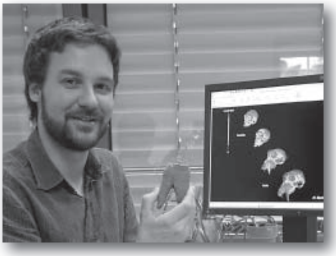
JASs Do it yourself
Journal of Anthropological Sciences
Vol. 86 (2008), pp. 193-198



Do it yourself

Virtual biomechanics: basic concepts and technical aspects of finite element analysis in vertebrate morphology

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Keywords - *Primate functional morphology, Finite element analysis, 3D image processing; Multibody dynamics analysis, Musculo-skeletal system, Teeth.*

Introduction

Morphologists have traditionally been studying the functional significance of variations in skeletal and tooth form among living and fossil vertebrates using a comparative-anatomical approach or by *in vivo* or *in vitro* experimentation. This has increasingly been complemented by computer-based or virtual biomechanics which includes three-dimensional (3D) quantitative image analysis of mineralised tissues as well as simulation and modelling techniques applied to the musculo-skeletal system such as finite element analysis (FEA) and multibody dynamics analysis (MDA). These modelling techniques have their origin in Engineering where FEA has been used for decades to predict structural performance of mechanical systems and MDA has been applied to derive reaction forces from a rigid-body motion of an object (Curtis *et al.*, 2008). In essence, FEA is a numerical analysis technique that is based on the principle of dividing a system into a finite number of discrete elements (in the shape of triangles, tetrahedrons or cubes). In turn, these elements are interconnected by nodes, thus forming a 2D or 3D mesh. In a structural analysis, engineering parameters of interest are stress, the applied force per unit area (Nm^{-2}), and strain which is the deformation within a structure (change in length/original length; unitless).

Recently, FEA has emerged as a useful modelling technique to study biological systems where experimental approaches are not feasible (see reviews on FEA and its use in vertebrate functional morphology by Richmond *et al.* (2005), Ross (2005) and Rayfield (2007)). In primate morphology and evolution, several studies have used FEA to assess the effects of differences in muscle load application, structural complexity and bone material properties on the stress and strain distribution and magnitude of the adult primate jaw and face during static biting (Ross *et al.*, 2005; Strait *et al.*, 2005, 2007; Kupczik *et al.*, 2007). On an ultrastructural level, FEA has been applied to test hypotheses about the functional significance of the size and the external and internal complexity of tooth structures with implications for interpreting dietary adaptations in the fossil human record (Macho *et al.*, 2005; Shimizu & Macho, 2007). In addition to modelling the stress-strain regime in existing biological structures, FEA enables the study of hypothetical morphologies to understand the adaptive significance of structures, such as the supraorbital browridges or the paranasal sinuses, by altering the size and shape of known skeletal morphologies. Moreover, a reverse engineering approach can be applied to deduce skull shape and bone distribution from the loading regime applied by iteratively removing elements below a defined stress threshold in a highly generalised FE model (Preuschoft and Witzel, 2004).

This guide is designed to provide an overview of the processing steps involved in constructing and analysing finite element (FE) models from 3D digital data. These four steps (preprocessing, solution, postprocessing, validation) are summarised in Figure 1. Moreover, the reader will be given information on where to obtain the input data as well as recommendations on software and hardware required for 3D image processing and FEA.

Finite element model building

The preprocessing stage involves the generation of a model prior to being converted into an FE mesh. Simple 2D or 3D geometric representations of the structure under study can be created and manipulated using computer-aided design (CAD) software. Many commercial FEA software packages (e.g. *ANSYS*, *Abaqus, MSC Patran/Nastran*) offer a CAD module as part of preprocessing. The CAD approach provides a relatively good control over the geometry used, particularly when assuming specific biomechanical models (e.g. the beam model). However, complex geometries such as

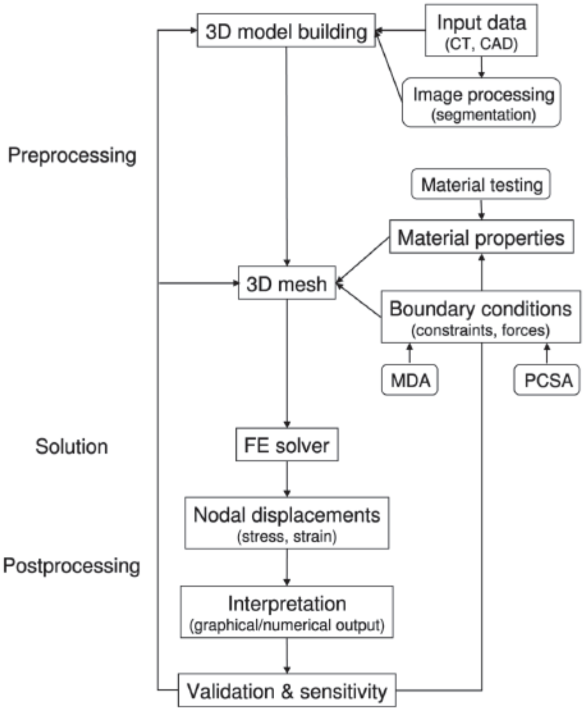

Fig. 1 - Flow chart of steps involved in FEA. Abbreviations: CAD=computer-aided design; CT=computed tomography; MDA=Multibody dynamics analysis; PCSA=physiological cross-sectional area of muscle.

cortical and trabecular bone may not be represented with sufficient precision.

Alternatively, the external and internal morphology of the skull, teeth and bones of the postcranial skeleton can be precisely captured by 3D imaging techniques such as laser surface scanning, computed tomography (CT), synchrotron X-ray or magnetic resonance tomography (Fig. 2A). Depending on the technology used, the resulting images vary in resolution between the millimetre and micrometre scale, which in the latter case even allows for analyses at the ultra and microstructural level. The process of extracting the objects of interest (e.g. the elements of the skull, the craniofacial sutures, the teeth) from a digital image and assigning them to discrete labels is called segmentation (Spoor *et al.*, 2000; Bruner & Manzi, 2006; Kupczik & Dean, 2008). There exists a plethora of segmentation procedures and algorithms, including semi-automatic approaches, available in open source software such as *ImageJ* and commercial 3D image processing packages (e.g. *Amira*, *Mimics*). Note the application of a particular segmentation algorithm is often case-dependent. For instance, one algorithm may work well when applied to scans of a single tissue (e.g. trabecular bone) but less well with scans containing more than one tissue (e.g. teeth in alveolar bone). Therefore, the segmentation may involve manual editing, which is often unavoidable when working with CT scans of both recent and fossil material.

Once the CAD process or the image segmentation has been completed, a triangulated 3D surface model can be generated which can be converted into an FE mesh consisting of tetrahedrons (Fig. 2B). Alternatively, an FE mesh can be voxel-based, i.e. each segmented voxel is directly converted into a cubic finite element (Fig. 2B). However, incompatibility between 3D image and FE file formats can be an issue as most 3D image processing software commercial FEA packages cannot import file formats other than CAD formats. In addition, only certain surface file formats (e.g. wrl; *hypermesh*) allow for the incorporation of more than one material. Some commercial software solutions exist which serve

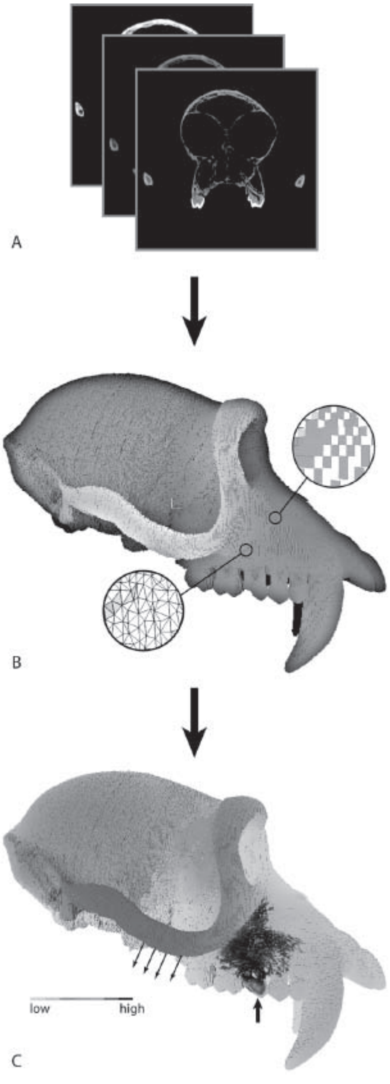

Fig. 2 - Processing steps in an FEA of a macaque skull. A: Finite element models can be built from a stack of CT images. B: Following segmentation of the CT stack, a 3D FE mesh is generated and may consist of tetrahedral (lower inset) or cubic (upper inset) elements which have specific mechanical properties (e.g. for cortical bone, enamel, dentine etc). C: Scaled contour plot showing regions of high and low compressive strains when loads are applied to the zygomatic arch (thin arrows). The thick arrow indicates the load exerted on the first molar. This FEA was conducted using VOX-FE (developed at the University of Hull and Hull York Medical School).

as an interface between the segmented images and the FE software (e.g. *Simpleware*), but large datasets cannot currently be processed due to computational limitations.

If CT image data from a clinical or a industrial microtomographic scanner are not readily available for FE model building, there are several dedicated databases that offer a wide range of high resolution CT datasets of vertebrate taxa including fossils for download (e.g. Digimorph, NESPOS). In addition, Betsy Dumont and Ian Grosse have initiated a web-based platform that enables the exchange and use of existing FE models (FEA in Biology Database). This is very useful for the FEA community not only because tested models are made available but also because this allows for the opportunity to cross-validate results using different analysis software and/or applying different boundary conditions (see below).

Material properties and boundary conditions

Following the mesh creation the mechanical properties of the elements of the objects involved must be specified. These are the Young's modulus of elasticity, Poisson's ratio and shear modulus. Their magnitude and orientation per element and spatial variation within the model has significant implications for the results of an FEA (Marinescu *et al.*, 2005; Strait *et al.*, 2005; Kupczik *et al.*, 2007). Paul Dechow and co-workers have obtained elastic property data of the cortical bone at several locations across the human, macaque and baboon skull by mechanical testing (Peterson & Dechow, 2003; Wang *et al.*, 2006) which have already served as a source for several FEA studies (Strait *et al.*, 2005; 2007). Moreover, the FEA in Biology Database lists published bone elastic property values for several skeletal elements of a variety of vertebrate taxa. In voxel-based models, the elastic property values can also be derived from the calibrated density values of CT scans assuming specific scaling relationships between CT numbers, bone density and elasticity (Marinescu *et al.*, 2005).

After assigning the material properties, the boundary conditions must be defined. These include the loads applied (e.g. muscle and bite forces; joint reaction forces) and the displacement constraints. In theory, all reaction forces in the model should be in equilibrium. However, this is often not the case and the model would be displaced. Thus constraints are required to anchor the model in space. Force estimates are available for the masticatory muscles for macaques (Ross *et al.*, 2005; Strait *et al.*, 2005, 2007). The estimates are derived from physiological cross-sectional areas of the masticatory muscles through dissection and take into account the muscle activity pattern of the individual muscles (Ross *et al.*, 2005). In the absence of bite and joint reaction force data for most non-human primates, a common approach is to constrain the teeth and the jaw joint in the assumed direction of load application, thus mimicking the reaction forces (Ross *et al.*, 2005; Strait *et al.*, 2005; Kupczik *et al.*, 2007). Alternatively, MDA allows for an estimation of bite and joint reaction forces and facilitates experimentation with muscle architecture and activity patterns (Curtis *et al.*, 2008).

Solution and postprocessing

Once the material properties have been assigned and the boundary conditions set, the model is ready to be submitted to an FE solver. This computes the displacements of the nodes and subsequently the resulting stresses and strains. Following this, in the postprocessing step these results can be presented and interpreted in the form of scaled contour plots or animated structural deformations (Fig. 2C). The processing time depends on the number of nodes and elements in the model. Since both the solution and the preprocessing stage (image segmentation and meshing) can require a great deal of processing power, a high performance workstation with multiple processors and a fast graphics board is recommended (see Table 1 for suggested hardware). High resolution voxel-based models with

Tab.1- Suggested hardware and software for a Virtual Biomechanics Lab.

Item	Description	Estimated costs (€)
PC workstation (minimum solution)	Multiple processors; 8GB and more RAM; OpenGL graphics board; 64 bit operating system	5,000-10,000
Software	3D image processing software (e.g. Amira 64bit version incl. mesh pack and very large datasets pack)	5,000
	File conversion software (e.g. Simpleware)	4,000 (annual)
	Multi-body dynamics analysis software (e.g. MSC MD Motion Bundle)	15,000
	FEA package incl. pre-, and postprocessing modules and solver (e.g. Abaqus license for dual-core jobs)	14,000 (annual)

element numbers in the order of 10^5 to 10^6 may even require a high performance computing cluster. Most commercial FEA packages run on both stand-alone PCs and clustered networks.

Validation and sensitivity

Any results from FEA have to be considered with caution unless a comparison with real-world data is provided. This means that the FE models have to be validated against independent empirical data to test their reliability (Marinescu *et al.*, 2005; Richmond *et al.,* 2005; Ross *et al.*, 2005; Strait *et al.*, 2005, 2007; Kupczik *et al.*, 2007). In FEA studies of primate craniofacial function published data on *in vivo* strain magnitude and orientation in macaques are available, which can be used to validate models. Likewise, *in vitro* experimental strain data are well suited for comparison with FEA results, because loading conditions can be exactly controlled for and strain gauge locations in the experimental specimens can be precisely recorded (Marinescu *et al.*, 2007; Kupczik *et al.*, 2007).

In addition to validation, it is also crucial to have an understanding of the sensitivity of the input parameters. A sensitivity analysis should test for e.g. the effects of changes of the applied loads, variations of the material properties or differences in the structure and size of the model on the modelling results (Ross *et al.*, 2005; Strait *et al.*, 2005; Kupczik *et al.*, 2007; Curtis *et al.*, 2008).

Concluding remarks

Virtual biomechanics and in particular FEA offer the opportunity to study vertebrate functional morphology in a non-invasive way and where traditional empirical methods cannot be applied. Crucial to the interpretation of FEA results is a test of the validity of the model and an assessment of the sensitivity of the input parameters. Most FEAs, that have tested hypotheses pertaining to the form-function relationship in adult skeletal form, have assumed static loading. Since biological systems are dynamic, future FE studies should assess the effects of growth and developmental changes in skeletal morphology on biomechanical performance and vice versa.

A last word of advice, the reader should be aware that any modelling technique can only approximate biological reality; it is not meant to replace it. If we knew all possible input variables and their effects on a biological structure, then there should be no reason to model it in the first place.

Acknowledgements

I am indebted to Paul O'Higgins for having given me the opportunity to work with FEA and for his continuous support. I would also like to thank Sam Cobb, Michael Fagan and Robin Feeney for comments and discussion.

References

Bruner E., & Manzi G. 2006. Digital Tools for the Preservation of the Human Fossil Heritage: Ceprano, Saccopastore, and other case studies. *Hum. Evol.*, 21: 33-44.

Curtis N., Kupczik K., O.Higgins P., Moazen M., & Fagan M.J. 2008. Predicting Skull Loading: Applying Multibody Dynamics Analysis to a Macaque skull. *Anat. Rec.,* 291: 491-501.

Kupczik K., Dobson C.A., Fagan M.J., Crompton R.H., Oxnard C.E., & O'Higgins P. 2007. Assessing mechanical function of the zygomatic region in macaques: validation and sensitivity testing of finite element models. *J. Anat.,* 210: 41-53.

Kupczik K. & Dean M.C. 2008. Comparative observations on the tooth root morphology of *Gigantopithecus blacki*. *J. Hum. Evol.*, 54: 196-204.

Macho G.A., Shimizu D., Jiang Y., & Spears I.R. 2005. *Australopithecus anamensis*: A Finite-Element Approach to Studying the Functional Adaptations of Extinct Hominins. *Anat. Rec.,* 238A: 310-318.

Peterson J. & Dechow P.C. 2003. Material properties of the human cranial vault and zygoma. *Anat. Rec.,* 274A: 785-797.

Preuschoft H. & Witzel U. 2004. A biomechanical approach to craniofacial shape in primates, using FESA. *Ann. Anat.,* 186: 397-404.

Rayfield EJ. 2007. Finite Element Analysis and Understanding the Biomechanics and Evolution of Living and Fossil Organisms. *Annu. Rev. Earth Planet. Sci.,* 35: 541-576.

Richmond B.G., Wright B.W., Grosse I., Dechow P.C., Ross C.F., Spencer M.A. & Strait D.S. 2005. Finite element analysis in functional morphology. *Anat. Rec.,* 238A: 259-274.

Shimizu D. & Macho G.A. 2007. Functional significance of the microstructural detail of the primate dentino-enamel junction: A possible example of exaptation. *J Hum. Evol.,* 52: 103-111.

Spoor F., Jeffery N. & Zonneveld F. 2000. Imaging skeletal growth and evolution. In P. O'Higgins & M. Cohn (eds): *Development, growth and evolution: Implications for the study of hominid skeletal evolution*, pp. 123-161. Academic Press, London.

Strait D.S., Wang Q., Dechow P.C., Ross C.F., Richmond B.G., Spencer M.A. & Patel B.A. 2005. Modeling material properties in finite element analysis: How accurate is accurate enough? *Anat. Rec.,* 238A: 275-287.

Strait D.S., Richmond B.G., Spencer M.A., Ross C.F., Dechow P.C. & Wood B.A. 2007. Masticatory biomechanics and its relevance to early hominid phylogeny: An examination of palatal thickness using finite-element analysis. *J Hum. Evol.,* 52: 585-599.

Ross C.F. 2005. Finite Element Analysis in Vertebrate Biomechanics. *Anat. Rec.,* 238A: 253-258.

Ross C.F., Patel B.A., Slice D.E., Strait D.S., Dechow P.C., Richmond B.G. & Spencer M.A. 2005. Modeling masticatory muscle force in finite-element analysis: sensitivity analysis using principal coordinates analysis. *Anat. Rec.,* 238A: 288-299.

Wang Q., Strait D.S. & Dechow P.C. 2006. A comparison of cortical elastic properties in the craniofacial skeletons of three primate species and its relevance to the study of human evolution. *J. Hum. Evol.,* 51: 375-382.

Associate Editor, Markus Bastir