New tools for analyzing biomechanical problems

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Abstract: The ability to automatically convert any 3D image dataset into high quality meshes, is becoming the new modus operandi for biomechanical analysis. New image processing and mesh generation techniques can now aid in the analysis of biological structures, particularly where the geometry is complex. Novel techniques have been developed for the automatic generation of volumetric meshes from 3D image data including image datasets of complex structures composed of two or more distinct domains and including complex interfacial mechanics. The techniques guarantee the generation of robust, low distortion meshes from 3D data sets for use in finite element analysis (FEA), computational fluid dynamics (CFD) computer aided design (CAD) and rapid prototyping (RP). Additional tools enable the incorporation of CAD models interactively within the image.

A range of different problems in biomechanics carried out for industry and academia using ABAQUS for the analysis will be illustrated including: modelling of the human eye; pre-clinical hip implant design evaluation (Stryker Europe); modelling of the lumbar spine for pre-clinical intervertebral implant design; and modelling biting stress of a pre-historic Colombian pliosaur based on fossil data (Cambridge University).

Keywords: Biomechanics, Palaentology, Orthopaedics, Spine, Medical Simulation.

1. Introduction

Current approaches to converting 3D images into meshes for use in FE (or CFD) analysis often necessitate time consuming processes and a gross simplification of the model geometry (Antiga et al. 2002, Cebral et al. 2001). Although a wide range of mesh generation techniques are currently available these, on the whole, have not been developed with meshing from segmented 3D imaging data in mind. Meshing from 3D imaging data presents a number of challenges but also unique opportunities so that a conceptually different approach can provide, in many instances, better results than traditional approaches. The majority of approaches adopted have involved generating a surface model from the scan data, which is then exported to a commercial mesher – a process which is time consuming, not very robust and virtually intractable for the complex topologies typical of image data. A more direct approach is to combine the geometric detection and mesh creation stages in one process. The process involves identifying volumes of interest (segmentation) and then meshing based on an orthotropic grid intersected by interfaces defining the boundaries. In effect, a base Cartesian mesh of the whole volume defined by the sampling rate is tetrahedralised at boundary interfaces based on cutting planes defined by interpolation points. The process incorporates an adaptive meshing scheme, which is fully automated and robust, creating smooth meshes with low element distortions regardless of the complexity of the segmented data (Tabor 2004, Young 2003).

2. Approach

A number of different case studies have been carried out in order to test the algorithms developed but these case studies have also been chosen to illustrate unique features of the proposed approach at different stages of the processing pipeline from image to model.

The steps involved in the generation and processing of finite element models based on medical imaging data are:

2.1 Scan and image processing

An extensive range of image processing and meshing tools can be used to generate highly accurate models based on data from any 3D medical imaging modality such as MRI, Ultrasound and CT. Features of particular interest include: Segmentation tools including Level Set Methodsl; Metal Artifact Reduction (MAR) Algorithms; Volume and topology preserving smoothing; Robust multi-part surface mesh/STL generation. The geometry of the structure is reproduced in the finite element mesh at sub-voxel accuracy;

2.2 Finite element model generation

The meshing algorithms automatically generate the mesh from the parts (masks) generated by image processing front end. As previously described, the approach used is based on post-processing a 'voxel' based mesh using techniques adapted from image processing to provide volumetric meshes with smooth outer boundaries for the different parts as well as smooth interfaces between parts. The meshing approach also incorporates an adaptive meshing scheme, which significantly reduces the degrees of freedom of the mesh. The approach implemented in the mesher has several advantages over traditional finite element model development techniques: Mesh generation from data sets of arbitrary geometric complexity; Topology and volume preserving smoothing algorithms; Meshing of multiple structures/regions of interest; Conforming contact surfaces/interfaces; User definable adaptive meshing; Material properties assigned to mesh based on signal strength

For volume data obtained from 3D imaging techniques the signal strength within an inhomogeneous medium (such as variable density foams, bone…) can, in some cases, be related to the material properties. Well-established and corroborated relationships have been obtained and used in the case of CT scan data of bone where the Hounsfield number can be correlated to the apparent density, which in turn can be mapped to the Young's Modulus (Schmitt et al. 2001, Zannoni et al. 1998, Ploeg et al. 2001, Taylor et al. 2002).

2.3 Export to ABAQUS

Nodes, elements, material properties, contact surfaces for any or all meshed parts may be exported to input-format files for a variety of FE and CFD packages. Where appropriate, elements may be exported as higher-order elements by the insertion of mid-side nodes.

3. Case study – Computer model of the human eye

3.1 Methodology

High resolution *in vivo* MRI scans of a 29 year Caucasian female was obtained using both a surface and a head coil on a Philips Gyroscan 1.5 Tesla imager. The following structures were segmented from the 3D data set by a Physician: the globe and optic nerve, the bony orbit, the eyelids and facial soft tissues, the extra-ocular muscles (Figure 1).

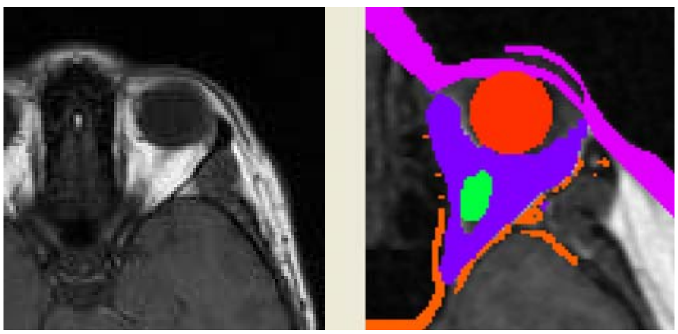

Figure 1. MRI scan (left) and segmentation (right) of the eye.

A number of finite element models were generated based on the segmented image data (Figure 2 left). Each structure was meshed with mixed hexahedral and tetrahedral elements. Interfaces between the different biological sub-structures can be either defined as merged (shared nodes across common boundaries/interfaces) or nodes can be de-coupled and contact surfaces spawned automatically at these interfaces. The contact surfaces are particularly robust as the master and slave contact faces are paired. Structures were either exported as volumetric meshes or as surface meshes as required (e.g. the bony orbit can most likely be modelled as a rigid structure defined by surface shell rather than as a volumetric mesh thereby providing some computational saving). Material properties within each and every structure could be straightforwardly assigned based on signal strength – in other words globe properties could be based on parent signal strength in image. However this facility is contingent on the user providing an appropriate relationship or mapping function between signal strength and material properties of interest – e.g. for the globe a relationship between signal strength and Young’s modulus. Such relationships can be obtained empirically through combined experimental and imaging tests. A number of analyses were carried out to demonstrate the robustness of the models for simulation purposes and these demonstrate the remarkable sophistication of biological models which can now be generated based on in vivo data.

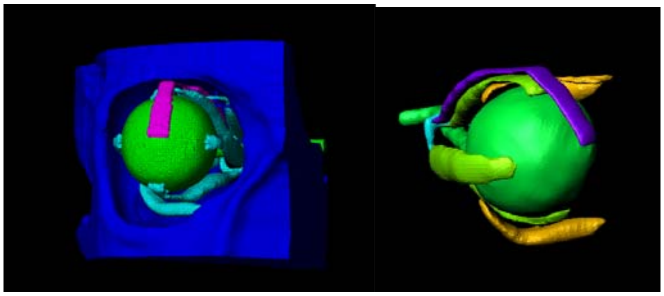

Figure 2. MRI scan (left) and segmentation (right) of the eye.

4. Case study – Total hip replacement (THR)

4.1 Overview

The University of Exeter, Stryker Europe and Simpleware Ltd collaborated to generate a post-operative model of an implanted hip. The study explores the possibility of generating pre-operative and post-operative patient specific models based on *in vivo* scan data. A case study was carried out to explore the feasibility of using clinical data for post-clinical structural evaluation of implant performance. An *in vivo* clinical scan of a patient fitted with a total hip replacement (THR) system was used to explore the influence of mesh density on the predicted response as well as the influence of the assumed contact model at the cup–implant interface.

4.2 Methodology

A CT scan of in-plane resolution 0.77 mm and slice-to-slice separation 1 mm was re-sampled and a Metal Artifact Reduction (MAR) filter applied. Six masks were created using ScanIP: (1) Pelvis, (2) Cement, (3) Cup, (4) Stem, (5) Cement mantle, (6) Proximal Femur (Figure 3).

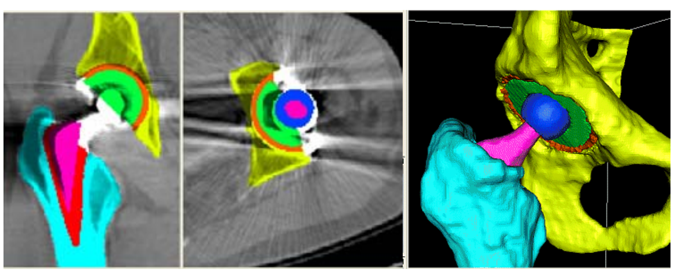

Figure 3. Segmentation and 3D view of hip with implant.

Based on the six segmented structures, two smooth models of different mesh densities were generated using ScanFE taking less than 3 minutes each. Additionally, a rapid prototyped model replica with the exact geometry as the FE mesh topology was generated. Using ABAQUS, material properties, boundary conditions and loads – including muscle forces – were applied. Nodes at the top of the pelvis and distal part of femur were defined in ScanFE. The response of the system was analysed under static loading conditions with a sliding interface at cup-implant interface (Figure 4). The total solution time (on an Intel 2.8 GHz) for the low density mesh was a little over 2 hours and 6 hours for the high density model.

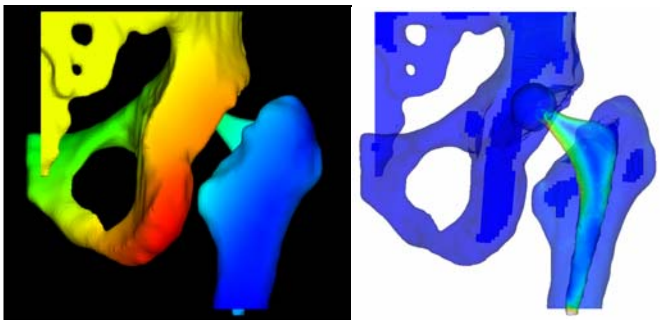

Figure 4. Finite element analysis in ABAQUS.

Validation of the techniques was carried out on cadaveric femora which were instrumented and loaded experimentally; strains at various locations were compared with those obtained from simulations run on FE models generated from CT scans of the same femora (Figure 5). With the *in vivo* model described here, due to the difficulty, experimental corroboration was not carried out, however numerical convergence studies provided strong evidence of the robustness of the solutions obtained. Two models with different mesh densities were generated and good agreement was obtained between stress and strain responses in all the different constituent components of the model (bone, cement, cup, implant).

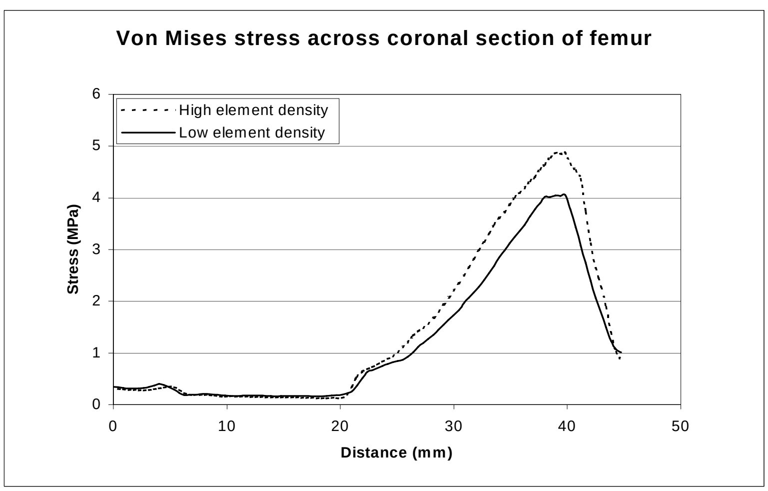

Figure 5. Comparison of stress across a section of femur for both high and low density models.

The models were also used to explore the influence of two different interface conditions at the cup-head: a no friction-sliding interface and an interface with cup and implant nodes merged. It was found that only the response in the neighbourhood of the implant-cup interface is appreciably affected by the assumed interface conditions.

5. Case study - Compression in the human spine

5.1 Overview

Work related injuries to the spine are becoming more commonplace in the UK with over one million people suffering from work induced musculoskeletal disorders of the lower back, each year. New image processing and mesh generation techniques can now aid in the analysis of such biological structures, particularly where the geometry is complex. Novel proprietary techniques have been developed for the automatic generation of volumetric meshes from 3D image data including image datasets of complex structures composed of two or more distinct materials.

5.2 Methodology

A 3D volumetric FE mesh of the human lumbar spine was generated from in vivo high resolution MRI scan data of 1mm in-plane and slice-to-slice separation. A mesh of 535 610 elements was generated in just twenty minutes and the anatomical details segmented in the model included five vertebrae, the annulus fibrosus, nucleus pulposus and the cartilaginous end plates (Figure 6).

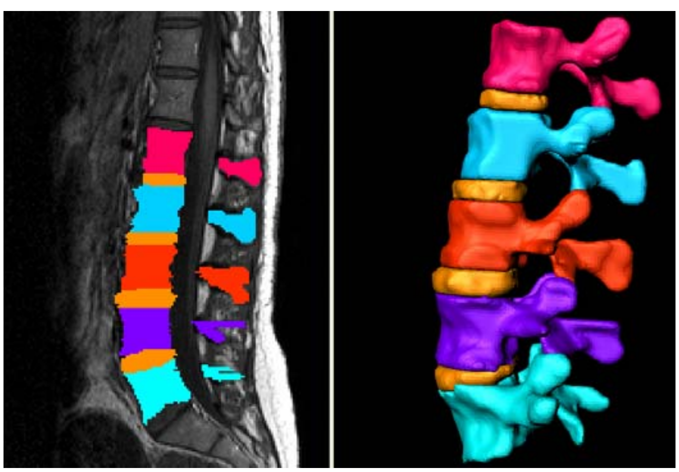

Figure 6. Segmentation and 3D view of lumbar spine.

A contact surface was created on the surface of the vertebrae between the superior and inferior articular processes. With a fixed boundary condition applied to the lower end of the model, a compressive strain was applied to the top of the spine in order to simulate a healthy young adult carrying a heavy load. The FE analysis took just under two hours on a pc and the results presented the individual pressure response of the components of the spine (Figure 7).

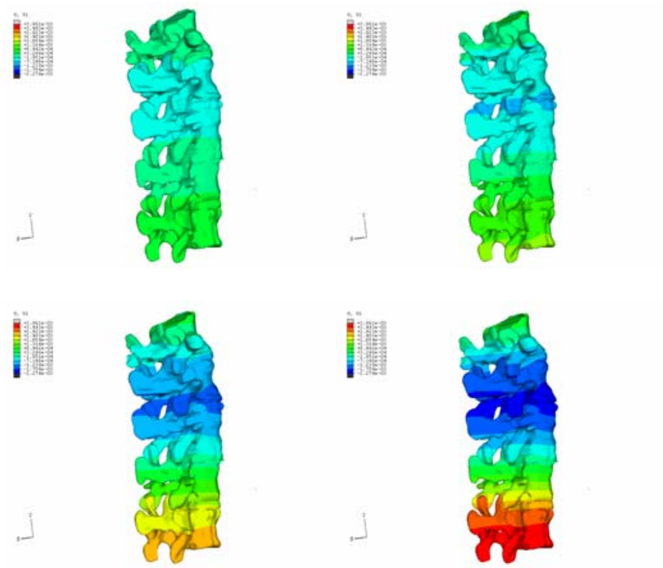

Figure 7. Compression of lumbar spine.

In this case, the tools have enabled the accurate analysis of compression to the human spine and will contribute significantly to the continued understanding of lower back pain.

6. Case study - Pre-historic Colombian pliosaur

6.1 Overview

A pliosaur is a type of reptile that lived during the Mesozoic Era (‘the age of the dinosaurs’ approximately 200-65 million years ago). However, unlike dinosaurs, pliosaurs lived in the sea, swimming using two pairs of hydrofoil shaped limbs. The Colombian pliosaur lived in the lower part of the Cretaceous period, approximately 130 million years ago. The remains of the pliosaur were found in the central Colombia, two hours drive northeast of the capital Bogota.

6.2 Methodology

The fossil was carefully removed from the limestone rock matrix using acetic acid, and the skull CAT scanned at the Royal Veterinary School in London, UK and ‘printed’ in 3-D using a rapid prototyper at the University of Alberta in Canada at a scale of 25%. The missing elements of the resulting prototype were reconstructed by comparison to the elements of the opposite side of the skull. This reconstruction was then CT scanned at the LifeScan centre in Brentwood, Essex. The completed digital model (Figure 8) was now ready to be used to investigate the bite force and mechanical strength of the skull.

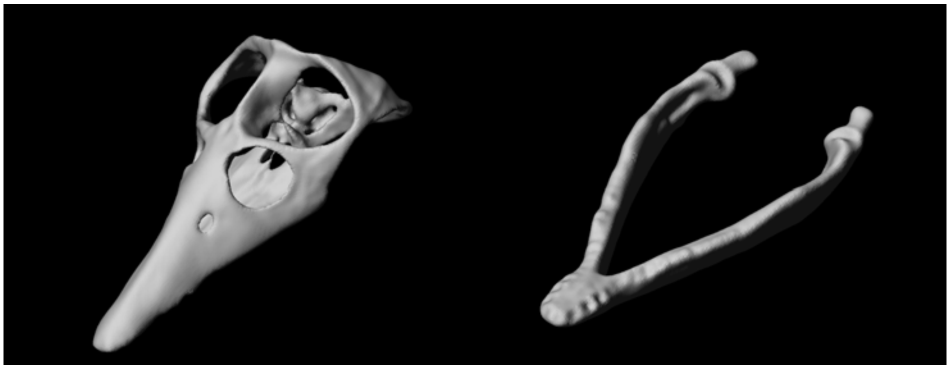

Figure 8. FE mesh of the cranuium (left) and mandible (right).

Pliosaurs became extinct at the same time as the dinosaurs, and left no living descendants, hence understanding their biomechanics and life styles requires more sophisticated analysis than mere comparison to living analogues (as can be done with, for instance, fossil crocodiles or lizards). The feeding strategies, bite strengths and many other life parameters of these large marine reptiles are therefore poorly known. Hence the only way to investigate these enigmatic reptiles is through modelling and other computer assisted techniques. The aim of this analysis is to provide insight into the biomechanics, and bite force (Figure 9) exerted by the jaws in order to better understand the feeding behaviour of this and other pliosaurs. In this way we can develop a deeper understanding of the ecological position of this pliosaur in the Lower Cretaceous seas.

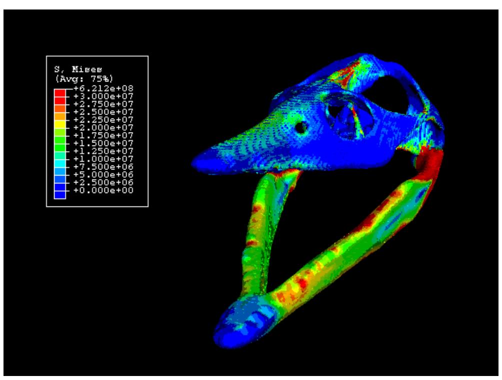

Figure 9. Von Mises stress distribution of bite force in ABAQUS.

7. Conclusions

The different case studies demonstrate the potential of the proposed approach for the generation of patient specific FE models based on *in vivo* and *in vitro* clinical scans. In spite of their complexity and sophistication, full FE simulations could be carried out on inexpensive and commonly available hardware platforms. The ease and accuracy with which models can be generated opens up a wide range of previously difficult or intractable problems to numerical analysis, including blood flow, material characterisation of nano-structural composites and patient-specific implant design. If the system is coupled with rapid prototyping hardware, it is also possible to produce a solid polymer or metal facsimile of the object in question – this part of the process can then be effectively conceived as a 3D photocopier.

8. References

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