06DHM-51

Automating the generation of 3D finite element models based on medical imaging data

Philippe Young
University of Exeter, Exeter, UK

G. Tabor[1], T. Collins[1], J. Richterova[2], E. Dejuniat[2], T. Beresford-West[2]
[1] University of Exeter, Exeter, UK
[2] Simpleware Ltd., Exeter, UK

ABSTRACT

Novel techniques have been developed to convert 3D image data, obtained from a range of imaging modalities (MRI, CT, Ultrasound, confocal microscopy), automatically into numerical meshes suitable for Finite Element (FE) and Computational Fluid Dynamic (CFD) analysis. The ease and robustness with which simulation models can be generated have opened the door to the generation of subject specific models, which can be used to explore a wide range of problems from impacts to the body through to vascular flows. A number of examples will be shown which illustrate the use of these techniques in digital human modeling, including simulation of the post-operative performance of a hip implant, modelling of the human foot, spine and eye, and CFD analysis of airflow through the human respiratory system. The different case studies illustrate how complex biological models can be modelled with not only a much higher degree of accuracy but also in a fraction of the time than was previously possible.

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 ([1], [2]). 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 [3 and 4].

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:

- Scan and image processing
- Finite element model generation
- Export to FE software

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 Methods
- Metal Artifact Reduction (MAR) Algorithms
- Volume and topology preserving smoothing
- Robust multi-part surface mesh/STL generation
- Accuracy of meshed topology/morphology is only contingent on image quality. The geometry of the structure is reproduced in the finite element mesh at sub-voxel accuracy

FINITE ELEMENT MODEL GENERATION

The meshing module automatically generates 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[1]

[1] 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 [5-9].

EXPORT TO FE SOFTWARE

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.

CASE STUDIES

TOTAL HIP REPLACEMENT (THR)

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 *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.

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 1).

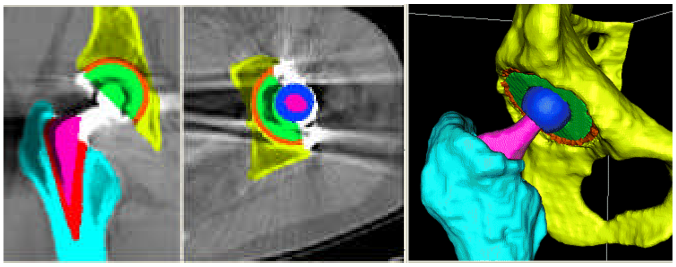

Figure 1 Segmentation and 3D view of hip with implant

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 2).

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.

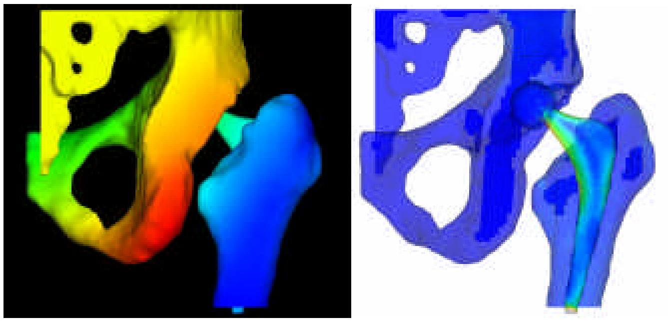

Figure 2 FE analysis in ABAQUS

Results

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 [10]. 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 3).

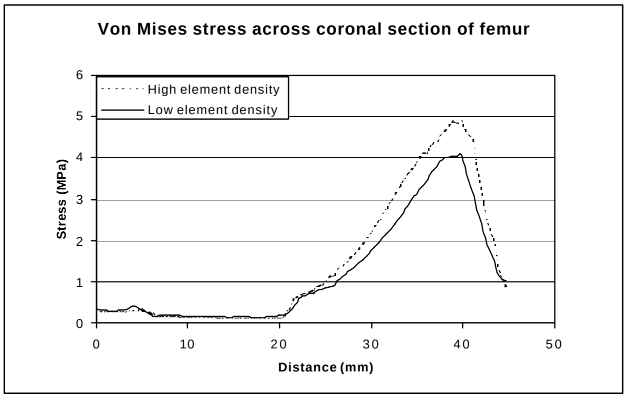

Figure 3 Comparison of stress across a section of femur for both high and low density models

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.

NUMERICAL MODEL OF THE HUMAN FOOT

Overview

The purpose of this study was to develop a complex skeletal model for finite element analysis of physical exercise, sports injury and footwear design. Such a model could generate simulations of normal and pathological foot behaviour.

Methodology

MRI scan data of a healthy human foot, was taken with in-plane resolution of 0.75 mm and slice to slice separation of 0.75 mm. A fully volumetric, mixed hex/tet finite element mesh, was generated whereby the model consisted of 26 foot bones, 51 ligaments and the plantar soft tissue. Material properties and loading conditions were assigned to the model according to the weight of a 70 kg human (Figure 4).

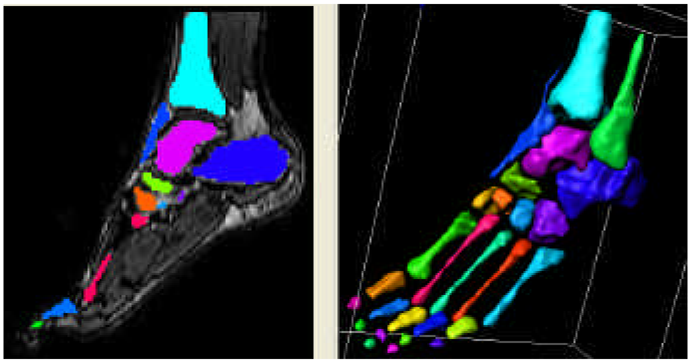

Figure 4 Segmentation and 3D view of the foot

A high quality, complex mesh of unprecedented sophistication was generated for use in FE analysis. The model was true to form and patient specific which opens the door to a vast array of applications in biomechanics. Parametric analyses can be performed to explore the function of different regions of the foot. Various treatment strategies could be simulated to quantify their efficacy in treating foot pathology. In addition to the obvious potential for sports injury and physical exercise analysis, it leads the way to mass customization of subject specific products such as running shoes or football boots.

COMPUTER MODEL OF THE HUMAN EYE

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 5).

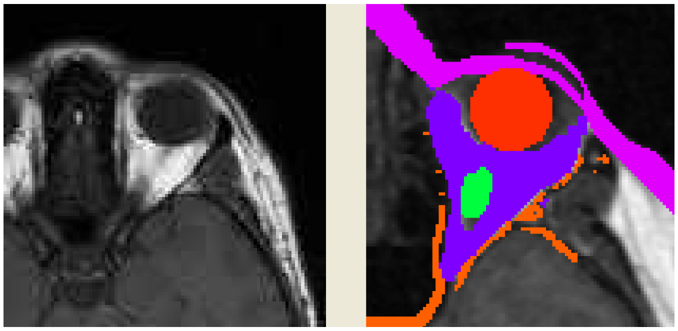

Figure 5 MRI scan (left) and segmentation (right) of the eye

A number of finite element models were generated based on the segmented image data using an in-house developed multi-part volumetric mesher (Figure 6).

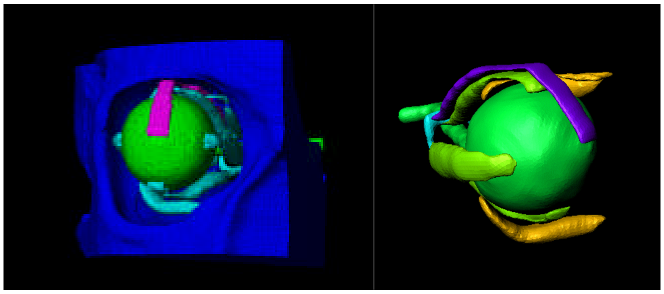

Figure 6 FE mesh of the eye

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.

COMPRESSION IN THE HUMAN SPINE

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.

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 7).

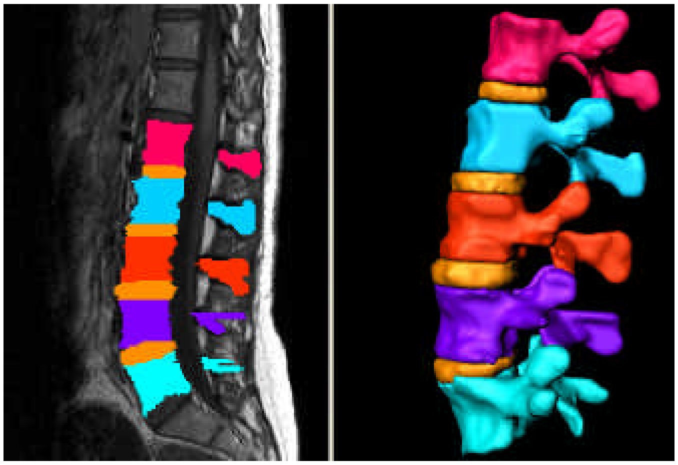

Figure 7 Segmentation and 3D view of lumbar spine

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 8).

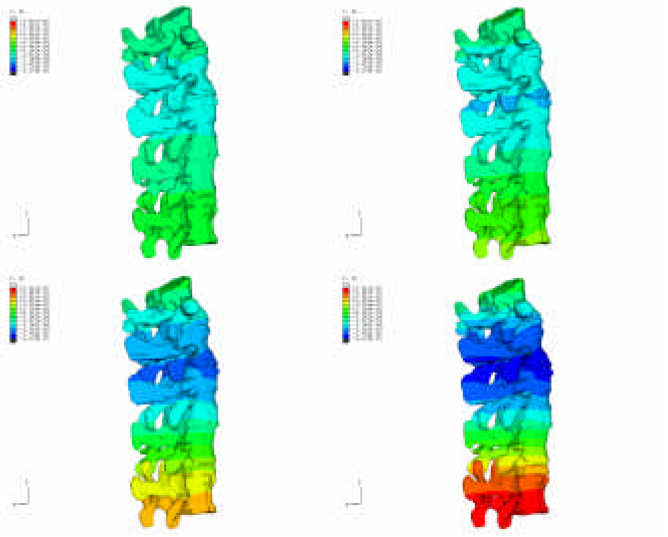

Figure 8 FE analysis of lumbar spine

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.

PARTICLE TRACKING THROUGH THE HUMAN RESPIRATORY SYSTEM

Overview

The study of airflow through the human respiratory system is a complex problem, which has in the past necessitated the use of numerical models based on grossly simplified geometry. This paper, presents the use of 3D imaging to generate a numerical model for the study of airflow through the human respiratory system using Computational Fluid Dynamics (CFD).

Methodology

A geometrically accurate CFD model was generated from high-resolution MRI scan data and analysis of the air flow through the human respiratory system was carried out. The aims of the study were (a) to compare an idealized geometry with that of a physiologically realistic geometry and (b) to examine the flow of air and track the trajectories of water vapour particles, through the human respiratory system using a CFD model created from MRI images (Figure 9). Calculations were performed using a turbulent flow rate of 0.0012 $m^3 s^{-1}$ under both aspiratory and expiratory flow conditions.

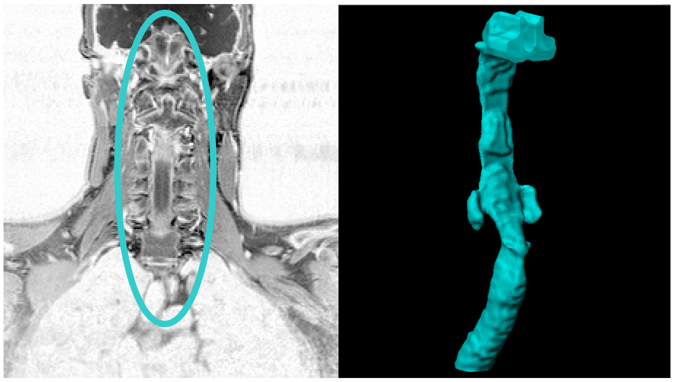

Figure 9 MRI scan (left) and segmented airways (right)

Results

There was very little agreement between the flow structures of the idealised geometry and that obtained from the MRI scan data. Re-circulatory regions in the idealised geometry were induced by sharp edges in the geometry but none of these re-circulatory flows were found to exist in the MRI geometry. It was evident that the curved features of the MRI geometry helped keep the flow attached to the walls thus preventing separation, re-circulation and adverse pressure gradients.

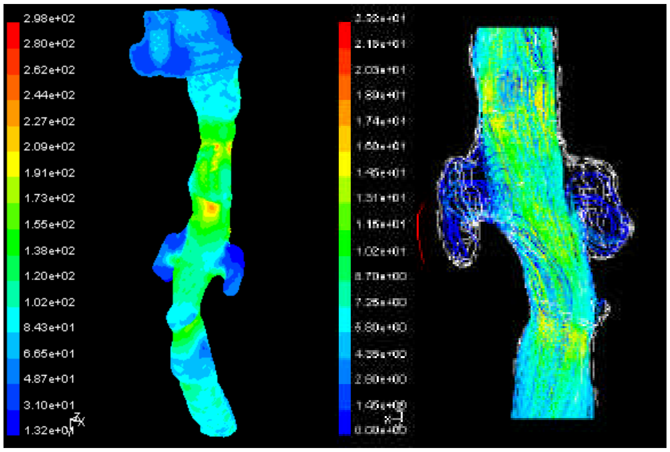

Figure 10 Contour plot - turbulence intensity (left) and pathlines – velocity (right)

A tracking study of a range of water vapour particles with a median diameter of 5.0 µm and a 90th percentile diameter of 10.0 µm, showed that small variations in particle diameter had little effect over the eventual destinations of the particles whereas the zones of the respiratory system with the most complex and curving geometry, trapped a higher percentage of larger diameter particles. These findings agree with those found previously in relation to vapour distribution from medical nebulizers (Figure 10).

CONCLUSION

The different case studies demonstrate the potential of the proposed approach for the generation of patient specific FE models based on *in vivo* 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.

ACKNOWLEDGMENTS

THE AUTHORS WISH TO THANK THE EPSRC (UK ENGINEERING AND PHYSICAL SCIENCES RESEARCH COUNCIL) FOR THEIR SUPPORT

REFERENCES

[1] L. Antiga, B. Ene-Iordache, L. Caverni, G.P Cornalba, and A. Remuzzi. Geometric reconstruction for computational mesh generation of arterial bifurcations from ct angiography. *Computerized Medical Imaging and Graphics*, 26:227 – 235, 2002.

[2] J.R. Cebral and R.Loehner. From medical images to anatomically accurate finite element grids. *Int.J.Num.Methods Eng.*, 51:985-1008, 2001.

[3] Gabor T., On Automating the Generation of CFD Models Based on 3D Data: Industrial and Biomedical Applications Conference Paper ECCOMAS 2004, Jyväskylä, Finland, 2004.

[4] Young P., Automating the generation of 3D finite element models based on medical imaging data: application to head impact, Conference Paper 3D Modelling, Paris, France, 2003.

[5] Schmitt J., Meiforth J., Lengsfeld M., Development of a hybrid finite element model for individual simulation of intertrochanteric osteomies. Medical Engineering and Physics, 2001, V. 23, pp.529-539.

[6] Zannoni C., Mantovani R., Viceconti M., Material properties assigned to finite element models of bones structures: a new method. Medical Engineering and Physics, 1998, V. 20, pp. 735-740.

[7] Ploeg H., Taylor W., Warner M., Hertig D., Clift S., FEA and bone remodeling after total hip replacement. BENCHmark, 2001.

[8] Taylor W.R., Roland E., Ploeg H., Hertig D., Klabunde R., Warner M.D., Hobatho M.C., Rakotomanan L., Clift S.E., Determination of orthotropic bone elastic constants using FEA and model analysis. Journal of Biomechanics, 2002, V. 35, pp. 767-773.

[9] Zannoni C., Viceconti M., Pierotti L., Cappello A., Analysis of titanium induced CT artifacts in the development of biomechanical finite element models. Medical Engineering and Physics, 1998, V. 20, pp. 653-659.

[10] Way G., Young P., Generation of a 3D finite element model of a femur with an implant based on 3D imaging data: A Feasibility Study. Technical Report Simpleware Ltd., 2003.

CONTACT

Dr Philippe Young, School of Engineering, Computer Science and Mathematics, University of Exeter, Exeter, Devon, EX4 4QF, UK.