Slikovna obdelava, virtualna rekonstrukcija in računalniško testiranje gradiv (tkiv)

Imaging, virtual reconstruction and computational material (tissue) testing

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Izvleček

Namen: *Zadnji napredki v strokovni programski in strojni opremi omogočajo zanesljive računalniške analize novih inženirskih gradiv in bioloških tkiv. Namen članka je predstaviti postopke, ki omogočajo natančno rekonstrukcijo in virtualno testiranje omenjenih gradiv.*

Metode: *Članek opisuje postopke in metode za računalniško rekonstrukcijo vzorcev na osnovi tridimenzionalnih (3D) slikovnih podatkovnih sklopov. Najprej so vpeljane različne metode za pridobitev 3D slikovnih podatkovnih sklopov (računalniška tomografija – CT, magnetna resonanca – MRI in ultrazvok – US), nato pa so predstavljene metode za virtualno rekonstrukcijo s pomočjo slikovne prepoznave slikovnih podatkovnih sklopov gradiv (tkiv). V ta namen je bil uporabljen sodoben računalniški*

Abstract

Purpose: *Recent advances in professional software and computer hardware allow for reliable computational analyses of new engineering materials as well as biological tissues. Therefore, the purpose of this paper is to describe the procedures allowing detailed reconstruction and virtual testing of such materials.*

Methods: *This paper describes the procedures and techniques for computational reconstruction of specimens, based on three-dimensional (3D) imaging data sets. First, different techniques of acquiring 3D imaging data sets (i.e., computed tomography – CT, magnetic resonance imaging – MRI and ultrasound – US) are introduced. Next the virtual reconstruction procedures for generated material (tissue) scans, based on image recog-*

programski paket ScanIP, ki omogoča samodejno virtualno rekonstrukcijo.

Rezultati: *Rekonstruirani modeli so virtualno preoblikovani in prilagojeni za posamezne potrebe oziroma diskretizirani (z uporabo +ScanFE in +ScanCAD) za nadaljnjo računalniško analizo, npr. za določitev njihovega odziva pri kvazi-statičnih ali dinamičnih obremenitvenih pogojih.*

Zaključek: *Članek zaključujejo trije praktični primeri: (i) rekonstrukcija in strukturna analiza zgornjega dela stegnenice (samostojno in z modeliranim vsadkom), (ii) rekonstrukcija ledvenega dela hrbtenice in (iii) rekonstrukcija in strukturna analiza neurejenih aluminijevih celičnih gradiv. Predstavljeni postopki zagotavljajo napredno in učinkovito metodo za širšo uporabo v medicinski in inženirski stroki.*

nition, are addressed. For this purpose the up-to-date commercial software package ScanIP was used, allowing for an automatic virtual reconstruction.

Results: *The reconstructed models can be virtually redesigned and adopted for special requirements or can be discretized (using +ScanFE and +ScanCAD) for further computational analysis, for example to predict their behaviour under quasi-static or dynamic loading conditions.*

Conclusions: *The paper concludes with three practical examples: (i) reconstruction and structural analysis of the proximal femur (alone and with a modelled implant), (ii) reconstruction of the lumbar spine and (iii) reconstruction and structural analysis of an irregular aluminium cellular material. The proposed procedures proved to be sophisticated and effective techniques suitable for a wide spectrum of medical and engineering applications.*

INTRODUCTION

Innovative solutions in image processing technologies and digitalization have been successfully introduced in many fields in the new millennium. In medicine, for example, daily work in hospitals depends on increased understanding of biological processes, accessed by sophisticated diagnostic tools that are helpful for medical staff and comfortable for patients (1). Different imaging procedures are available, such as computed tomography (CT), magnetic resonance imaging (MRI) and ultrasound (US), all relying heavily on modern software solutions (2). These modern imaging techniques can be used also outside the biomedical field, most notably in engineering, for the virtual design and computational testing of modern material structures, based on virtually reconstructed three-dimensional (3D) imaging data sets. Modern computer assisted examination procedures enable wider connection with and interaction between many scientific and professional fields in the applied sciences (3, 4). The acquired imaging data sets form the basis for proper image recognition and virtual reconstruction, which has been an area of great interest in the computational simulation community for decades. Several robust algorithms are already widely available (5). However, the development of most of these techniques has not considered the need for meshing from segmented 3D imaging data. Mesh generation from 3D imaging data presents a number of challenges but also a unique opportunity for producing more realistic and accurate geometrical descriptions of the computational domain.

The purpose of this paper is to describe the procedures allowing detailed and reliable reconstruction and virtual testing of biological tissues as well as many engineering materials. First, the different techniques for acquiring 3D imaging data sets – CT, MRI and US – are reviewed. Then, the virtual reconstruction procedures for the generated scans, based on image recognition, are discussed, based on the up-to-date commercial software provided by Simpleware (6).

The paper concludes with three practical examples based on 3D image scans: (i) reconstruction and structural analysis of the proximal femur (alone and with a modelled implant), (ii) reconstruction of the lumbar spine, and (iii) reconstruction and structural analysis of an irregular aluminium cellular material.

Three-dimensional data imaging of materials

"Medical imaging" is the term often used to designate a set of techniques that noninvasively produce images of internal aspects of the body but which are also used in broader scientific and industrial applications, for example, for advanced material characterization. Some of these widely used imaging techniques are briefly described in this section.

Ultrasound

US examination has been used in modern medicine and other scientific and industrial areas for many years. US uses piezoelectric transducers to produce high-frequency sound waves (7, 8). After the basic Brightness-mode (B-mode) technology became well established (9, 10), US was given fresh impetus with the development of volumetric imaging (3D and 4D US, Fig. 1). 3D and 4D US images depend on modern software and equipment sending sound waves at different angles; 2D US sends the waves straight down, to be reflected straight back. The advantages of US are accessibility and safety, enabling frequent repeating scans without any risk for patients.

Magnetic Resonance Imaging

MRI fundamentally differs from US and CT examinations and this has a significant impact on data acquisition, data processing and image evaluation (11). MRI uses physical and biochemical properties of tissues (protons) for image formation and therefore produces insight into physiological and pathophysiological processes within tissues (Fig. 2). Its advantages are noninvasiveness and avoiding ionizing radiation. Its disadvantages are the duration of the examination and its inability to be used if any implanted metal parts are present, such as pacemakers. In recent years developments in hardware have improved its technical possibilities, allowing for extended movement range, multiple receiving

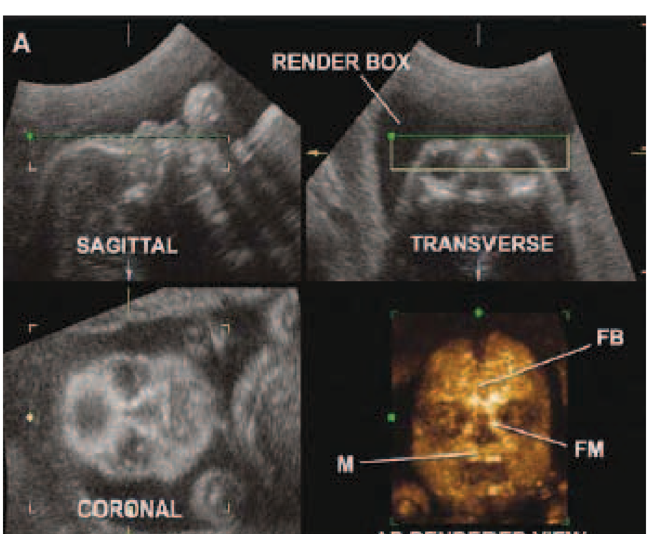


Figure 1: State-of-the-art 4D ultrasound representation of a fetus

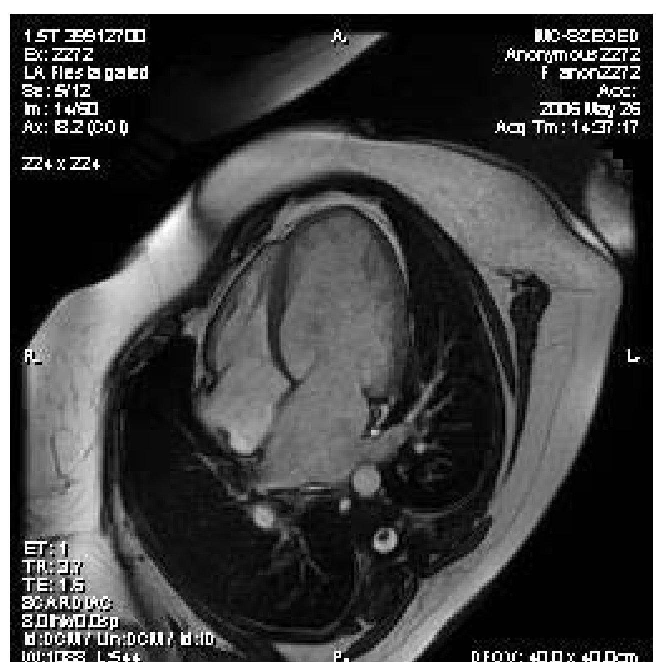


Figure 2: MRI representation of the cardiac ventricles

channels and whole body surface coil coverage. Furthermore, an increased number of simultaneously available receiver channels enables ”parallel imaging”, which can be used to enhance spatial resolution at a constant acquisition time. Development of new software and faster protocols allow for MRI of the whole body in just one step.

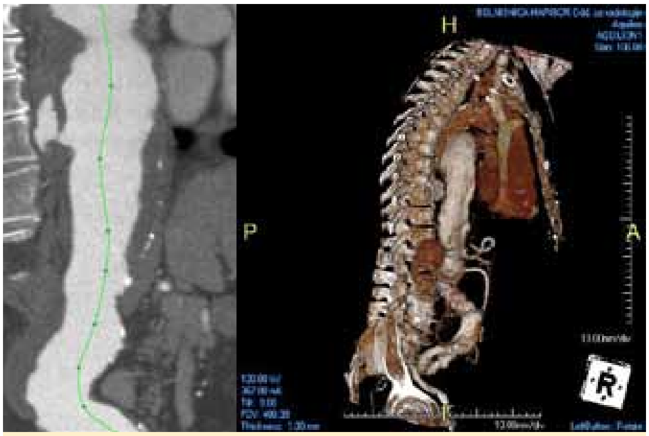


Figure 3. Multi-planar reconstructions (left) and volume rendering technique (right) based on MRCT

Multi Row Computed Tomography

Since its introduction in 1970s CT has developed and become an important and frequently used diagnostic examination procedure. The introduction of the spiral technique and some new technical solutions, such dual source and multi row detectors, allow for simultaneous acquisition of data and assessment of larger body areas (12-14). The relevant scanning parameters are tube voltage (kV), tube current (mAs), rotation time and PITCH (table advancement per rotation divided by the collimated detector width). All these parameters can influence the total radiation exposure (13, 15). Typically, 64 slice scanners are used; however, the latest developments allow for scanners with up to 256 slices and increased speed of gantry rotation. Multi row computed tomography enables faster data acquisition with shorter duration of reconstruction and improves volume resolution, especially in the *z*-axis (isotropic resolution).

Post-processing of collected data allows for extraction of clinically relevant information from the enormous amount of data collected and for modification of the initial axial images to make them more useful to observers. There are several post-processing techniques available, such as: multi-planar reconstructions (MPR) which can be generated from the volume data set reconstructed from a stack of axial images (Fig. 3, left); maximum intensity projection (MIP), a visualization method that projects only the highest-intensity voxels (volumetric pixels) encountered by each ray to reconstruct a 2D image; and the volume rendering technique (VRT), which uses all the voxels of the volume data to create a 3D image based on the density of each voxel (Fig. 3, right) (however, the software is very important for this and some difficulties with precise and detailed reconstruction of the volumetric samples remain to be solved). Because of the complexity of normal and pathological anatomy, the reconstruction process has not been fully automated, therefore qualified experts are needed to evaluate the raw images.

Overall, MRCT is a very efficient diagnostic examination method but with a high radiation exposure for the patient (a disadvantage that does not apply to investigations in other scientific and industrial fields).

Virtual reconstruction and mesh generation

The commercial software provided by Simpleware Ltd. was used for virtual reconstruction and computational model discretization (6). The software was originally developed for finite element (FE) analysis of bones, for both stress and vibration analysis (16). A user friendly graphical interface was developed later, creating commercial software which is available as two different modules – ScanIP (virtual reconstruction and CAD modelling) and +ScanFE (FE discretization) (17). A third module, +ScanCAD, has been introduced recently to provide extra functionality, allowing to import an implant represented in a standard CAD format and interactive positioning of the import inside an existing scan (18, 19). Direct export to a number of major commercial computer-aided engineering (CAE) software is possible, thus providing more flexibility for researchers in the computational biomechanics community.

Image-based virtual reconstruction

The majority of up-to-date image based reconstruction (mesh generation) techniques involve first generating a surface model (either in a discretized format, e.g. triangular mesh, or a continuous parametric surfaces format, e.g. bi-cubic patches or NURBS) and then using a third-party tool to create the volume mesh (20, 21). Such an approach, referred to as the CAD-based approach, can be very time consuming, is not very robust and is virtually intractable for complex topologies. A more direct approach is to combine the geometric detection and mesh construction in one process. This involves identifying volumes of interest (segmentation) and then generating the volumetric mesh directly based on a 3D Cartesian grid intersected by interfaces defining the boundaries.

Techniques for the CAD-based approach do not easily allow for more than one domain to be observed because the multiple surfaces generated are often non-conforming, with gaps or overlaps at boundary interfaces. Identifying inter-domain boundaries first and then generating surface meshes independently (using a surface mesh generation technique on parametric or discretized surfaces) would be a less reliable option since meshes on closely neighbouring domains may intersect. Another, more advantageous tactic is the direct approach (i.e. topology reservation) combining boundary detection with the surface and volume mesh generation.

Direct approach for image-based mesh generation

The direct approach algorithm combines the boundary detection and mesh generation tasks in one process. It also accommodates models with arbitrary numbers of parts and complex geometry/topology. Surface and volume meshes are generated based on an arbitrary 3D array of voxels provided via a stack of 2D slices in the 3D image; in other words, the construction of a CAD representation is a stepping stone in the conversion process that can be bypassed completely.

Image processing

Digital images obtained by medical scanning technology are sometimes of poor quality. Sources of noise (e.g. metal artefact in a typical CT scan) and/or a low level of contrast between adjacent objects/tissues can cause severe consequences for other steps downstream. In such cases the image may need to be pre-processed before proceeding to the segmentation step. Image processing is an active area of research and filtration and smoothing algorithms are under constant development. However, several filtration algorithms are already embedded in ScanIP, namely, metal artefact reduction, a recursive gaussian smoothing filter, gradient anisotropic diffusion, curvature anisotropic diffusion, and a min/max curvature flow filter (6, 17, 19).

Segmentation

Segmentation is an essential step for any image based mesh generation technique. It is the stage where voxels/pixels that belong to different objects are identified and grouped together in different sets referred to as masks (representing different materials). Several techniques are available to carry out such a task either in a fully/semi automated manner or interactively using bitmap painting tools. One of the most practical techniques is thresholding, which uses two different values of the greyscale to define a range that determines which pixel is ”in” and which pixel is ”out” of the area of interest. The threshold range can be adjusted interactively while all pixels within the range are shown in one colour that differs from pixels outside the range (see Fig. 4 for an example of a model with multiple parts). More advanced segmentation algorithms, such as Flood Fill, Connected Region Growing and Level Set, are also available (6, 17, 19).

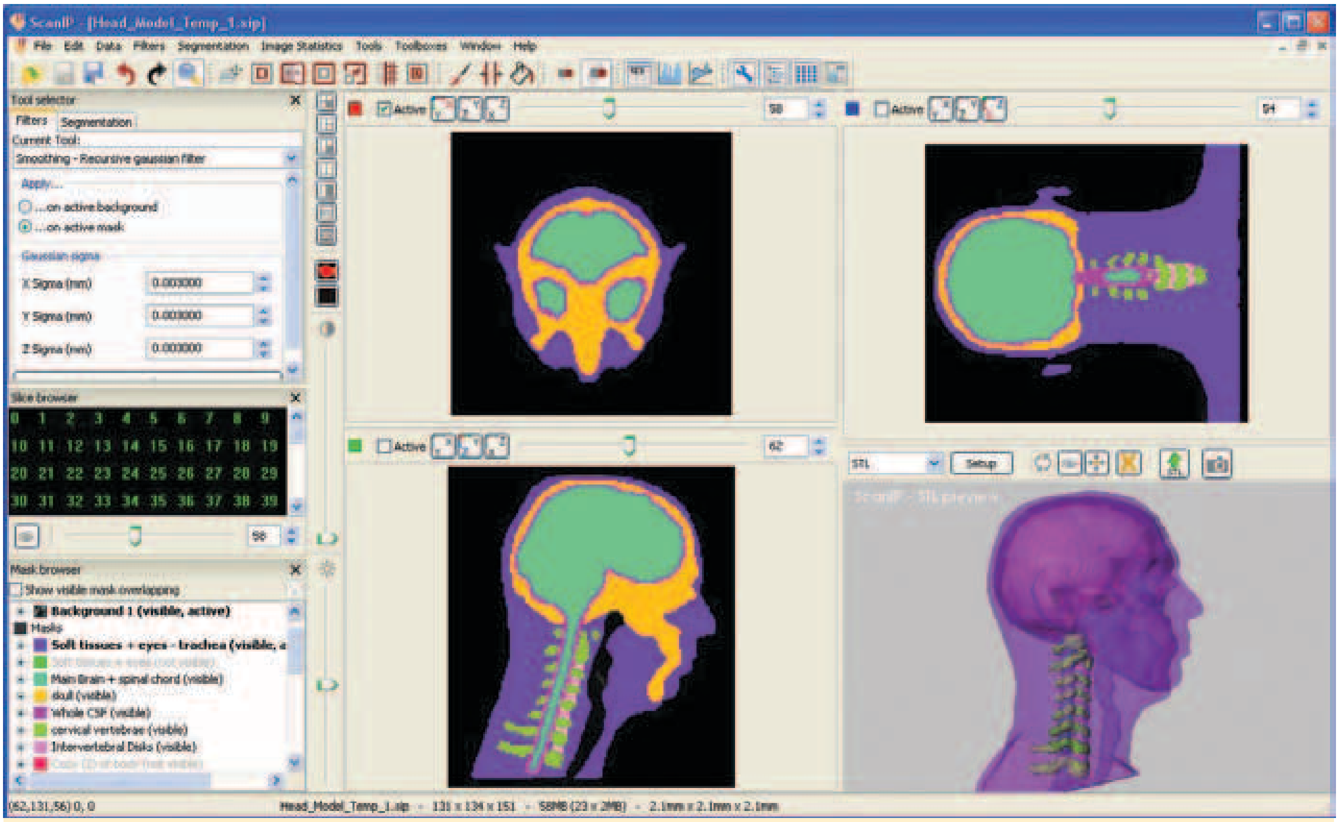
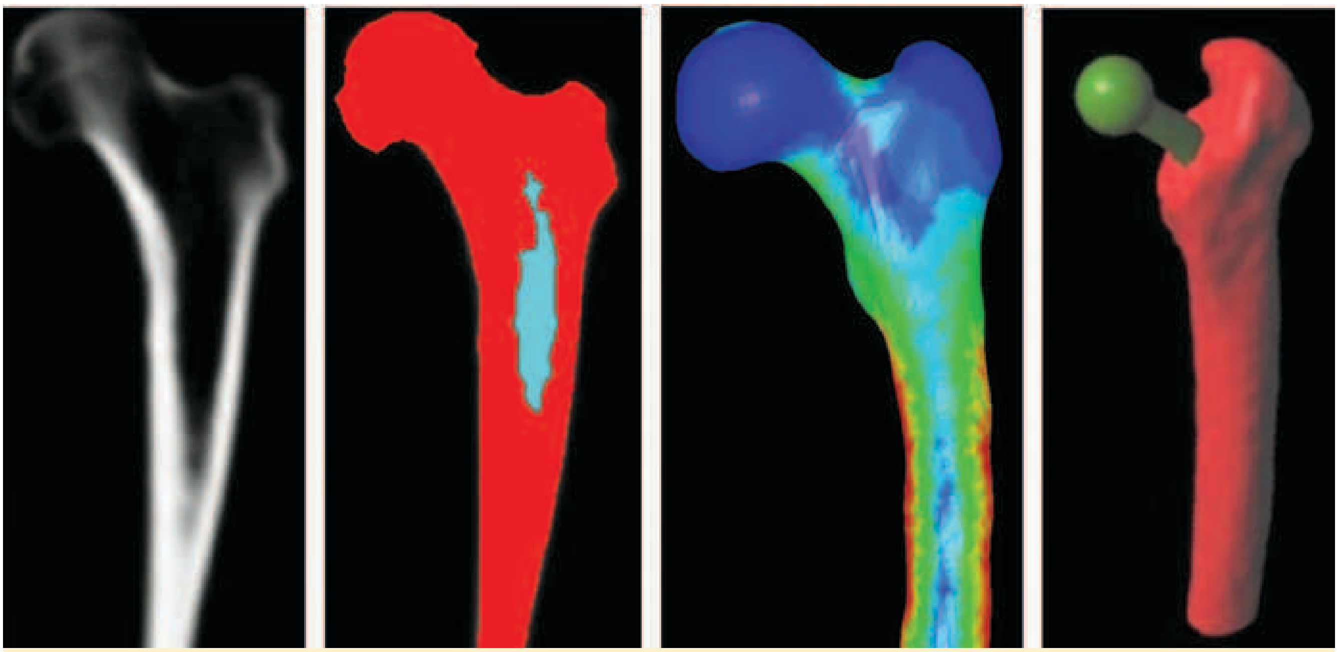


Figure 4. A screenshot of ScanIP with a typical CT scan of six objects (masks) represented by different colours in the three main planes and 3D view

Surface and volume finite element mesh generation

The segmented volumes of interest are then simultaneously meshed based on an orthotropic grid intersected by interfaces defining the boundaries. The base Cartesian mesh of the whole volume defined by the sampling rate is "triangulated/tetrahedralized" at boundary interfaces which are based on cutting planes and defined by interpolation points. Smooth boundaries are obtained by adjusting the interpolation points: (i) by setting points to reflect partial volumes or/and (ii) by applying a multiple material anti-aliasing scheme. The process, which incorporates an adaptive meshing scheme, results in either a mixed tetrahedral/hexahedral mesh or a pure tetrahedral mesh. The adaptive meshing scheme preserves the topology but reduces the mesh density. Towards the interior of the model the mesh is produced by agglomerating hexahedra into larger hexahedra and generating transitional tetrahedra. The approach is fully automated and robust, creating smooth finite element meshes with low element distortions regardless of the complexity of the segmented data. It allows for an arbitrary number of different volumes to be meshed. That neighbouring subdomains share a common cutting surface ensures a node to node correspondence at the boundaries between different meshed volumes, thus satisfying the geometrical constraints at the boundaries (avoiding gaps or overlaps).

Furthermore, for volume data obtained from 3D imaging techniques the signal strength within an inhomogeneous medium (e.g. variable density foams, bones) 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 from bone, where the Hounsfield number has



a) Proximal femur CT scan
b) virtual reconstruction
c) computational structural analysis – red colour represents high stress areas
d) virtual hip implant placement

Figure 5.

been correlated to the apparent density, which was then mapped to Young's Modulus (22-24).

EXAMPLES

In this section two medical and one engineering application are shown, where imaging, virtual reconstruction and computational analysis were successfully employed.

Reconstruction and structural analysis of the proximal femur

The digital image data set acquired by CT was used for virtual reconstruction of the proximal femur: the reconstruction was later used for computational analysis of its behaviour under compressive loading.

The set of CT scans (Fig. 5a) was reconstructed using the FloodFill segmentation procedure in ScanIP (Fig. 5b), where a voxel size of 0.7 x 0.7 x 0.7 mm was set (19). Figure 5b illustrates that the reconstruction technique enables viewers to determine different areas (material densities) separately. +ScanFE was then used for spatial discretization of the reconstructed proximal femur model, with extra surface smoothing and mesh quality optimization, comprising approximately 60,000 tetrahedral elements. The linear elastic FE model was exported to conduct further structural dynamic analysis. The dynamic compressive load was vertically (z-axis) applied to the top of the bone head, while the lower part of the analyzed bone was fixed in all three coordinate directions. Dynamic analysis was performed using the explicit finite element code LS-DYNA (25-27). The results of the computational analysis in the form of deformation and stress representations are shown in Fig. 5c, where the tensile and compressive stresses due to bone buckling are clearly visible.

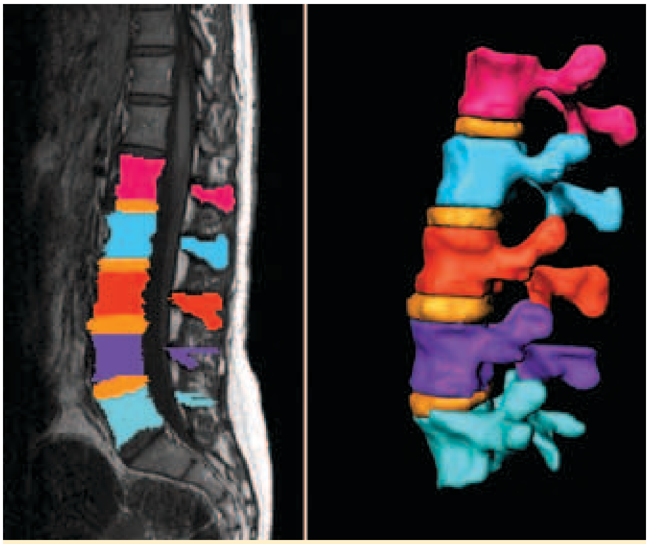


Figure 6. Segmentation on a 2D slice (left) and 3D view of the lumbar spine (right)

With additional use of +ScanCAD an implant was added and correctly positioned (using rotation and translation) to the reconstruction, from which the head of the proximal femur was removed (Fig. 5d). Such a hybrid model can also be used for computational analysis in order to optimize the implant's efficiency.

Reconstruction of the human spine

An in vivo MRI scan of the human lumbar spine with high in-plane resolution and 1 mm slice-to-slice separation was used to construct a volumetric FE mesh of approximately 550,000 elements.

Appropriate segmentation techniques (Threshold, Paint and FloodFill) and smoothing were applied to reconstruct the computational model (19). The anatomical details included five vertebrae, the annulus fibrosus, nucleus pulposus and cartilaginous end plates (Fig. 6). The contact surfaces were extracted automatically based on the surfaces of the vertebrae between the superior and inferior articular facets (Fig. 7).

To simulate a healthy young adult carrying a heavy load a compressive strain was applied to the top of the spine, while the lower end of the model was fixed.

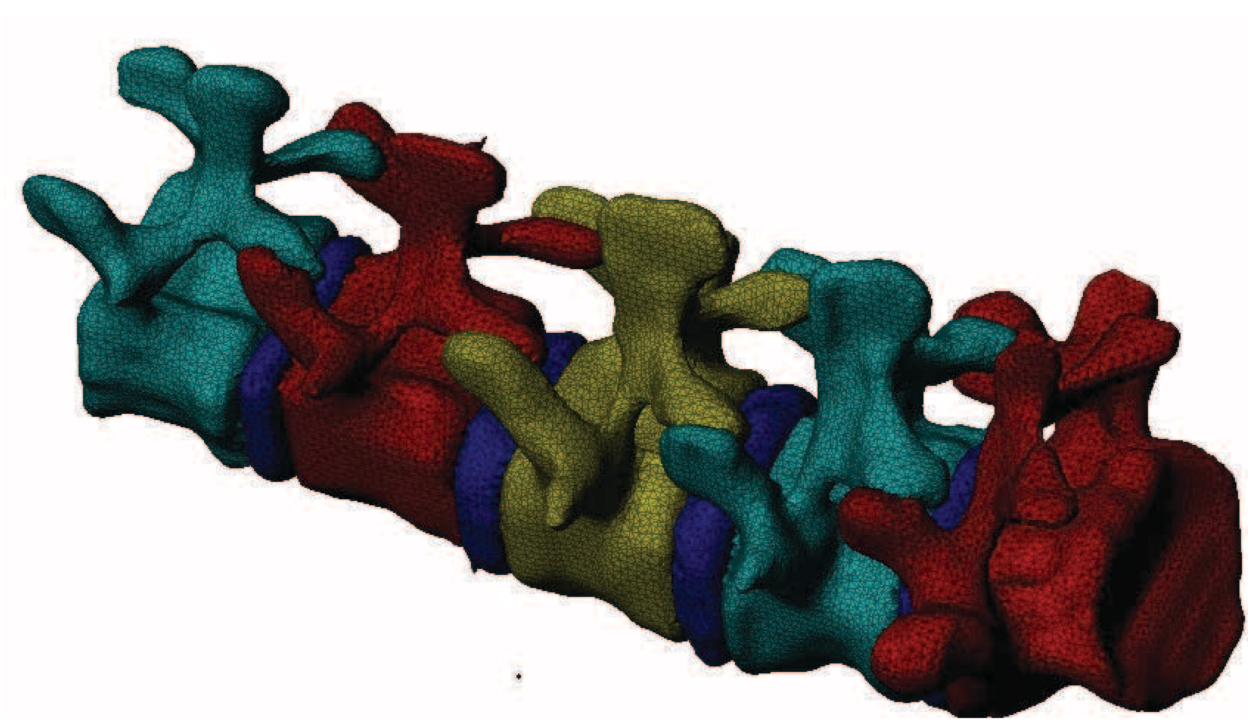
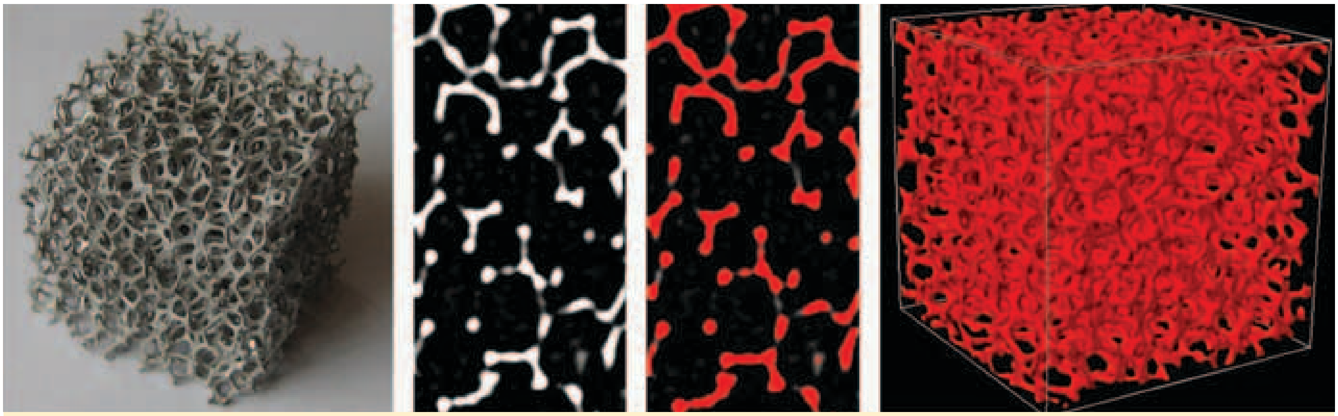


Figure 7. Solid finite element mesh with contact surfaces between vertebrae and discs



a) Alluminium cellular material *b) CT scan* *c) virtual reconstruction* *d) solid CAD model*

Figure 8.

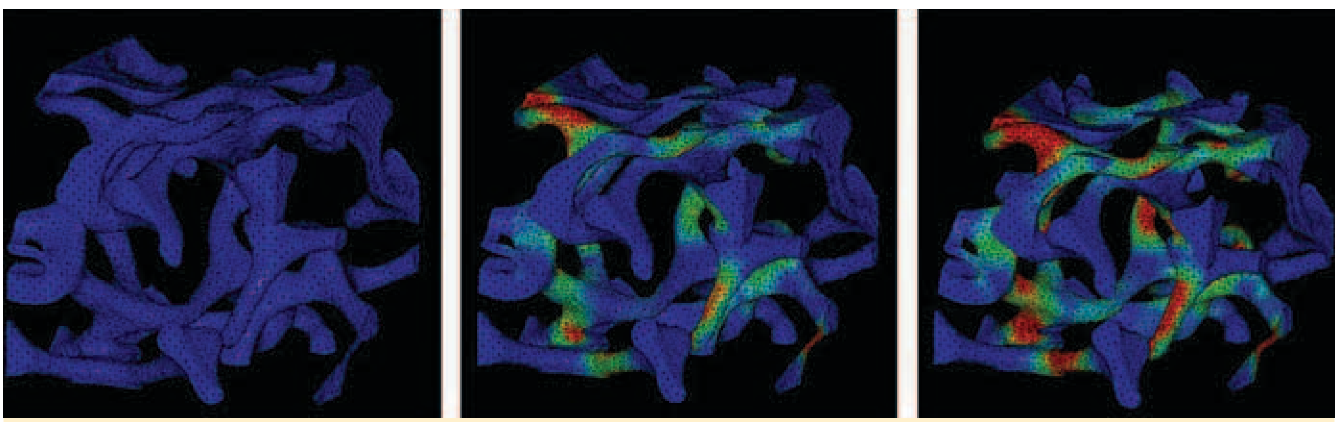


Figure 9. Structural analysis of the aluminium cellular material

The results of a quasi-static FE computational analysis confirmed the described procedure as being a promising application in a variety of areas of medicine.

Reconstruction and structural analysis of aluminium cellular material

This example details a dynamic structural analysis of a realistic aluminium cellular material (metallic foam) used in many engineering applications (e.g. impact energy absorption), whereby the realistic irregular geometry of the computational model was acquired using CT and virtual reconstruction (4, 28). The aluminium foam Duocell (Fig. 8a), cube shaped with dimensions 40 x 40 x 40 mm, was scanned at the Department of Radiology, University Medical Centre Maribor, using the MRCT Toshiba Aquillion 64 with a rotation time 0.35 s (allowing imaging a body area of 300 mm in 3 s with a slice width of 0.5 mm). To achieve proper CT contrast it was necessary to determine the optimal tube current settings and scanning mode. After an initial study the following scanning protocol was used: 64 x 0.5 detector configuration, 80 kV, 60 mAs, PITCH 1.5, 0.5 mm beam collimation and 0.3 mm slice thickness. The 140 CT images (Fig. 8b) were then imported into ScanIP. Using the threshold segmentation technique and adjusting the lower value to 130

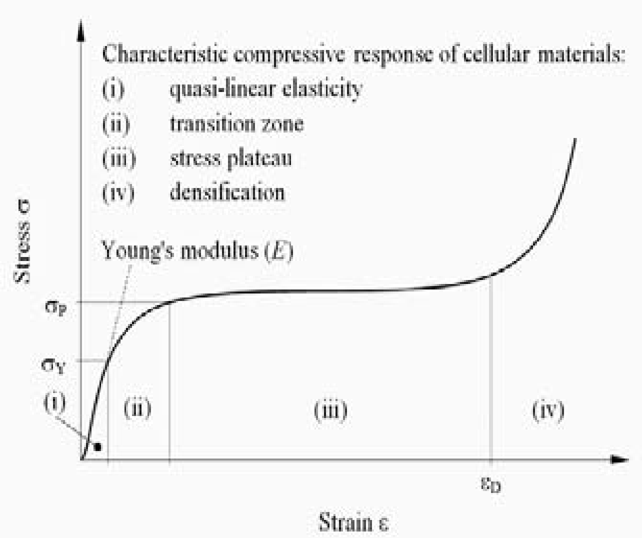


Figure 10. Characteristic compressive response of the cellular material

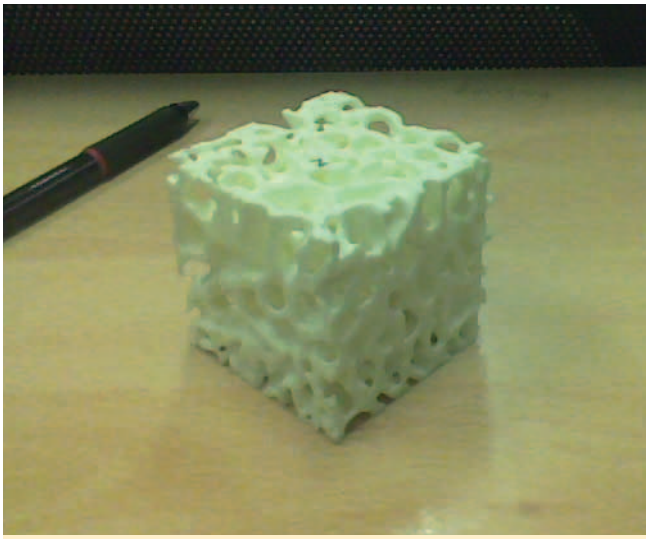


Figure 11. Magnified bone structure produced by rapid prototyping

and the upper value to 255, the mask (Fig. 8c) for the virtual reconstruction was set in order to obtain the solid CAD model (Fig. 8d).

A part of the generated CAD model was discretized by ScanFE using approximately 130,000 tetrahedral finite elements with elastic-plastic strain rate dependent material properties. A dynamic compressive load, achieving a strain rate of 100 s^{-1}, was applied to the upper surface of the cellular material. The model was constrained at the lower surface in the loading (vertical) direction. A single surface contact algorithm was selected (26, 27). Explicit dynamic finite element analysis was performed using the engineering code LS-DYNA. The results of the structural analysis in the form of cellular material deformations are shown in Fig. 9, in which the stress concentrations during loading can be clearly observed.

The results of the structural analysis of this irregular cellular material indicate a typical compressive stress-strain behaviour (Fig. 10) of the cellular structures (28-31).

An additional advantage of the procedure employed is the possibility of manufacturing reconstructed solid CAD models using a rapid prototyping technique, as already suggested by Cosmi (32). Figure 11 shows a computational and experimental analysis of magnified human bone structure. Reproduction of reconstructed models with irregular topologies allows for advanced validation possibilities in material and structural characterisation.

CONCLUSIONS

The paper describes the procedures and techniques for virtual reconstruction and computational testing of biological and metallic materials, based on 3D imaging data sets obtained by CT, MRI or US. Virtual reconstruction and mesh generation of digitalized material (tissue) scans using the image recognition software is describe in detail. The reconstructed models were virtually redesigned and adapted to special requirements or discretized for further deformational analysis to precisely observe their behaviour under quasi-static or dynamic loading conditions. Additionally, the paper describes three working examples, based on 3D image data sets: (i) reconstruction and structural analysis of the proximal femur (alone and with an implant), (ii) reconstruction of the lumbar spine, and (iii) reconstruction and structural analysis of an irregular aluminium cellular material. The reconstructed models allow for simultaneous comparison between computational simulations and experimental testing of reproduced models with rapid prototyping techniques. The proposed procedures and methods prove to be effective and can be fitted to a wide spectrum of medical and engineering applications.

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