Novel combination of reverse engineering and rapid prototyping in medicine

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The technologies of reverse engineering and rapid prototyping are emerging as useful new tools in medicine. One application is of particular interest in orthopaedic, dental and reconstructive surgery. It involves the imaging, modelling and replication (as a physical model) of a patient's bone structure. The models can be viewed and physically handled before surgery, which is of great benefit in evaluation of the procedure and implant fit in difficult cases. The technology promises lessened risk to the patient and reduced cost through saving in theatre time. A case study is presented, involving hip replacement in a patient who had experienced severe bone loss through osteoporosis. Such applications are a further step towards the development of a new generation of customized bone implants.

The technologies respectively labelled reverse engineering and rapid prototyping have developed rapidly in recent years.[1] While the major applications are found in the fields of engineering and design, these technologies are emerging as useful new tools in medicine.[2–6] Reverse engineering and rapid prototyping are of particular interest in skeletal repair, where physical models of bone structure are produced for planning surgical procedure and evaluation of implant fit. The process typically involves imaging bone structure using computer axial tomography (CAT) scans, conversion of the two-dimensional slice data to three-dimensional computer-aided design (CAD) models and manufacture of physical models using any of a number of rapid prototyping (RP) technologies. The primary concerns at present include interpretation of images, discrimination of tissue types and dimensional accuracy. This article describes current capability through a case study involving hip replacement in a patient who had experienced severe bone loss through osteoporosis.

Capturing geometric shapes of existing physical parts or components in a format that can be used for further engineering is the basis of reverse engineering. Two- or three-dimensional data are subsequently used with some form of post-processing. There are at present some 30 shape-digitising methods that can be broadly grouped as contact or non-contact. The contact group includes touch probe and destructive methods, whereas the non-contact group includes laser, computer axial tomography, optical and ultrasonic methods. For medical applications, CAT (X-ray) and magnetic resonance imaging (MRI) are particularly important as data acquisition methods for reverse engineering.

The two-dimensional CAT or MRI slice images are converted to three-dimensional data, in the case described here as Stereolithography type (STL) files for rapid prototyping purposes. The STL file is a triangulate surface wire mesh of the CAD model and is the basis of subsequent rapid prototyping. The accuracy of models generated from CAT or MRI data is subject to the interpretation of images, discrimination between tissue types, dimensional accuracy and spacing of slices.

Various rapid prototyping systems have been developed in recent years, with regular improvements in quality and production speed. Most systems involve deposition or machining of material in sequential, patterned layers gradually to build a structure. The benefits of rapid prototyping include enhanced visualization capability, reduced development cost, early detection of design flaws and limited part testing prior to conventional prototyping. In the medical field, early applications centred on models of bone or other tissue which are used by surgeons to plan and perform complex procedures before actual surgery. Apart from obvious benefits to the patient, the approach promises significant savings through reduced theatre time and risk. Areas where this technology has been successfully applied include maxillofacial reconstruction, pelvic fractures, spinal trauma, orthodontic surgery, nose reconstruction and models of soft tissue structures such as cardiovascular systems.

For the work reported here, a commercial Stratasys fused deposition modelling machine was used to produce models in ABS polymer. The RP process normally starts with a three-dimensional solid or surface CAD model, or in this case two-dimensional CAT or MRI images, converted to STL type format. The STL model is sliced into horizontal layers and parameterized. Parameters include road width, slice thickness, fill type, and start and end positions.[1] Construction of the model then proceeds according to these criteria. Temporary structures are sometimes added to the model during manufacture to allow deposition of unsupported or suspended sections. These are removed on completion of the model.

Case study: hip replacement

A patient required replacement of the left hip joint. The procedure was complicated by the fact that the bone had deteriorated badly as a result of osteoporosis. A study was conducted with the orthopaedic surgeon to capture the bone structure of the hip region to facilitate assessment of the viability of the procedure.

The patient was examined using a Toshiba Spiral X-Vision/GX CAT scanner. The clinic then prepared a three-dimensional rendering of the scanned area. The information was prepared in two forms, as 3-mm-thick slices at 3 mm and 0.5 mm spacing, respectively, to evaluate the difference. The surgeon was particularly interested in the left side of the pelvis. For a successful hip replacement, sufficient bone structure is required at the posterior side of the acetabulum. It was clear from the CAT scan that the anterior side of the pelvis did not have sufficient bone structure.

The two-dimensional slice information, three-dimensional rendering and film images were supplied to verify mutual consistency. In the x-y (slice) plane, dimensional agreement between film and images after scaling was approximately 1–2 %. Along the z-axis the uncertainty was greater, approaching the slice thickness in magnitude.

Bone particles were incorporated in the soft tissue at the site and discrimination between viable and suspended bone was difficult, even using a cadaver left side pelvis as reference. The pelvis and femur

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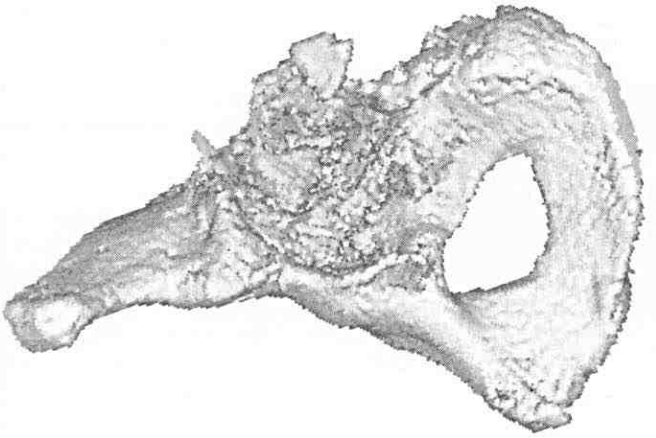

Fig. 1. Rendering of viable bone structure of the damaged pelvis following data reduction.

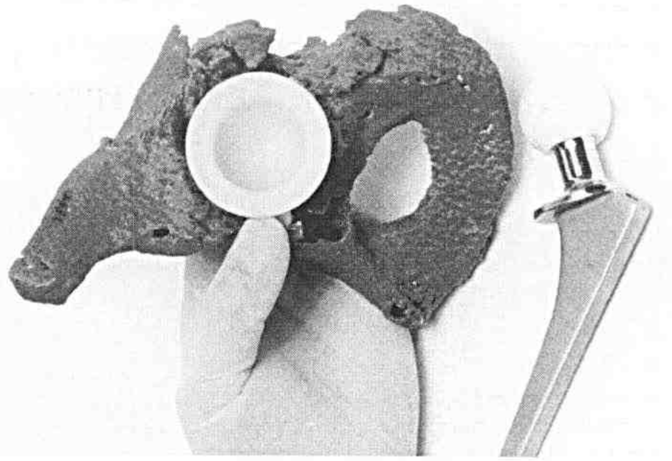

Fig. 2. Completed model with acetabular cup and femoral component to give scale.

were hardly recognizable in certain areas. The data were processed and subsequently reviewed with the surgeon prior to replica production. A rendering of the viable bone structure is shown in Fig. 1, indicating the extent of osteoporotic bone loss.

Data were converted to STL format and used with Stratasys QuickSlice™ software to generate horizontal slices with automatic support generation in an SML (machine control) file. The structure was grown in ABS polymer at 0.25-mm layer thickness and finished by removing supports (Fig. 2). The model was delivered to the orthopaedic surgeon, who used it for detailed planning and verification of the surgical procedure.

Implication for new generation implants

Applications beyond bone modelling are already envisaged. While present work is focused on the replication of bone structure as physical models, it is possible to produce not only such models but also custom implants to fit the modelled defects. This requires incorporation of a further new technology, that of prototyping directly in bioceramic material. Early work in this regard is described in a companion article.[6] The primary concern here is the internal design of the bioceramic structure, which has to meet biological rather than dimensional requirements for bone and tissue ingrowth.[7,8] The achievement of external dimensional accuracy is a matter of engineering.

At a more advanced level is the loading of biologically active molecules such as bone morphogenetic proteins onto implants.[9] This technology is not yet commercially available but holds the promise of greatly promoting healing of skeletal defects. In combination, the various technologies described here represent a comprehensive advance in bone tissue engineering.

The accuracy of conversion of two-dimensional image slices to three-dimensional CAD models is a limitation at present. The use of dense scan spacing, in this case 0.5 mm as opposed to 3 mm spacing, was considered beneficial in this regard. Film images were captured along with digital scan data and these were used to verify the accuracy and dimensions of rendered images. Access to scanning equipment for data retrieval requires careful management, as these instruments are in great demand, and data should ideally be captured in a parallel system or retrieved during off-peak hours. The turnaround time and cost are still high, due mainly to the absence of automated procedures, but a significant reduction in both turnaround time (about three days) and cost appears possible in routine application.

The studies reported to date indicate that although the application of rapid prototyping technology in medicine is relatively underdeveloped, it is already justified in certain cases.

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The world is too big for us. Too much is going on, too many crimes, too much violence and excitement. No matter how hard you try, you get behind in the race. It's a strain to keep pace. Science empties its discoveries on you so fast that you stagger beneath them.
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