A New Method for Biomodelling and Rapid Prototyping of Human's Hard Tissues as Substituting Prostheses

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Abstract: In recent years, 3D imagination of human's organs has become feasible by digital image processing techniques and algorithms via CT or MRI images. In this study, a new method for reverse engineering and biomodelling of hard tissues by CATIA cloud points' concept has been considered. Comparing with the current softwares such as BioBuild or Mimics, the proposed method has demonstrated its easiness of implementing and modelling, final model's high accuracy, easiness of data exchanging with the rapid prototyping systems and reduction of need for having anatomical background to interpret the CT or MRI images.

Keywords: Digital Image Processing, Femur, Biomodelling, Rapid Prototyping, Hard Tissue, Virtual Reality

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1 INTRODUCTION

3D modelling has been designated as the basis of modern computer-based manufacturing technology, since synchrony in executing different phases of design and manufacturing procedures has caused time reduction of part's simulation and development. A 3D model plays key role in the part's life cycle. Among various modelling concepts, just 3D models are complete and perfect and represent the final product's clear overview. Among the main techniques for modelling, solid modelling is the key factor for integrating the design and manufacturing process. Today, solid modelling is the most certified and confidential way for various aims such as biomedical applications. Biomodelling is a new branch of biomedical prototyping technology that provides:

1- Convenience of interpreting and removing the uncertainty and ambiguity in the final interpretation of medical images.
2- Possibility of proper trauma's diagnosing and healing the casualties.
3- Direct recognition of tissue's various anatomical aspects for the surgeons and implant designers.
4- Time reduction of prostheses manufacturing, increasing the accuracy, cost cutting and decreasing the risk of damage to the patients. These prostheses have direct effect in the reconstruction of initial and natural conditions of the patient, especially in maxillofacial operations and cranioplasty.
5- Simulation of the surgery conditions, practicing and checking of all the aspects before the real operation and planning to choose the best road map.
6- A contribution to accelerate the healing procedure, based on adopting the proper curing methods.

Based on the above-mentioned items, a new method for reverse engineering and biomodelling of hard tissues by the CATIA cloud points concept has been considered and presented in this study.

Comparison with the current softwares like BioBuild or Mimics has shown the new method's easiness of implementing and modelling, final model's high accuracy, simplicity of data exchanging with the Rapid Prototyping (RP) systems, and suppression of requirement for having the anatomical background to interpret the CT or MRI images.

2 BACKGROUND

The discovery of the diagnostic values of X-Rays opened a way of studying internal anatomy without any physical intervention to the organs. Plain X-Rays were quickly accepted for displaying the skeletal pathology. Major advance came with the introduction of Computed Tomography (CT) in 1973 [1]. By means of the new technology, neurosurgeons could study direct cross-sectional images of intracranial soft tissue of tumours.

The illustration of neuroanatomy was a great advance in comparison with Angiography, Myelography and Pneumo-Encephalography methods. Being widely used in neurosurgery, CT was applied soon in other fields as well. The usage of X-Rays was followed by the application of Ultrasound and later, Magnetic Resonance Imaging (MRI). These advances in medical imaging have created volumes of complex data and speciality for interpretation of such information.

3D imaging has been developed to narrow the communication gap between radiologists and surgeons. By using 3D imaging, a vast number of complex sliced-form images can be combined into a single 3D image.

Biomodelling is the generic term that describes the ability to replicate the morphology of a biological structure in a solid substance. Specially, biomodelling has been defined as the process of using radiant energy to capture morphological data on a biological structure and the processing of such data by a computer to generate the required codes to manufacture the structure by the RP tools.

Real Virtuality (RV) is the term used to describe the creation of solid reality from virtual imagery. In contrast, RV creates a computer-synthesized experience for the observer without a real basis. In medical applications, biomodelling is used to create an anatomical RV [2].

Biomodels are truly remarkable and exciting tools in the practice of surgery. D'Urso et al. have shown that biomodels can have 5 major roles in craniofacial surgery [3-5]. The roles are listed as:

1- For surgical team, as a tool for communication and educating the patient.
2- To assist surgeons with diagnosis and surgical planning.
3- For the rehearsal and simulation of surgery.
4- For the creation of customized prostheses.
5- For the accurate placement of implants.

3D imagination of human's organs and biomodelling is enabled via the combination of 3D medical imaging with RP. Specially speaking, biomodelling is the science of converting scanned morphological data into exact solid via specialized software and digital layer-based fabrication systems. Continuous increase in different eras for patient's data acquisition, image processing algorithms and the biomodels production, has made biomodelling more practical. By introducing CT scanning, applications in 3D imaging for surgery

didn't emerge in clinical practice, until the concept was sufficiently advanced in early 1980s. Alberti proposed the concept of producing physical models from CT scans in 1980, but the technologies for processing the anatomical data and producing the biomodels were both limited at that time [6].

Marsh et al. to White proposed different methods (e.g. from the stacking of life-size aluminium or polystyrene cut-outs of CT slice bone contours to the use of three-axis Computer Numerically Controlled (CNC) milling) to create two-part moulds for prostheses' model casting [7-10]. By the advent of five-axis CNC milling, Zonneveld et al. proposed a new method for constructing more complex bio models without moulding [11]. It was evident that the complex anatomical geometries were not ideally suited even for the five-axis milling machines, and particularly for replicating the geometries' internal structures.

In other hand, the high-resolution 3D CT scanning also presented significant challenges. High radiation doses, long image acquisition, and reconstruction times were among the factors which limited the use of 3D imaging for biomodelling. Kalender et al. proposed the applicability of volumetric medical imaging and slip-ring CT scanning to the surgery [12], [13]. This innovation enabled high-speed volumetric imaging with acceptable resolution for practical 3D imaging. In parallel, Aoki et al. presented simultaneous advances in 3D Magnetic Resonance Angiography (MRA) [14].

D'Urso et al to Derbin et al. proposed the 3D rendering techniques for voxel-based data that allowed the shaded surface display of image volumes to demonstrate anatomy in a life-like 3D view via surface shading with a virtual light source [7], [15-17]. Lorensen et al. presented another approach called "Marching Cubes" [18]. This algorithm was devised to perform surface rendering on an image volume representing the object via a triangulated surface mesh. Such a triangulated mesh was identical to the surface mesh used to describe the CAD objects for Stereolithography via STL format.

Developments in the volumetric image acquisition and 3D image processing were made parallel to each other, when Hull released the first commercial RP system [19].

The new SLA device allowed submillimeter-layer-based fabrication of arbitrary complex shapes. Markovich et al. reported the implementation of 3D CT with SLA device for biomodelling aspects [20]. The SLA technique with its layer builder algorithm showed superior advantages to the milling method in biomodelling purpose. As each SLA layer thickness was 0.25mm, each 2.0mm CT slice had to be replicated 8 times to allow the biomodel to be built up from this data. Further work was done on the contour-based (or so-called "Direct Layer Interface") approach that utilized an algorithm to produce a "Stack" of interpolated RP contours in a Stereolithography Contour (SLC) file. This algorithm eliminated the need for any 3D surface description, as well as solving the "In Between Z Plane" slice interpolation problem by using the cubic interpolation.

The new algorithm was first used in the Mimics software and the major benefit of this approach was that large image volumes could be processed at high resolution, and the resultant contour files described a 3D anatomical object more efficiently than a STL surface file for equivalent resolution.

Barker put forth a new procedure for medical image processing [21]. This approach allowed advanced 3D visualization via voxel gradient shading volume rendering. The new technique also utilized to the development of Cranio-Maxillofacial modelling and then was implemented to the developments of BioBuild software.

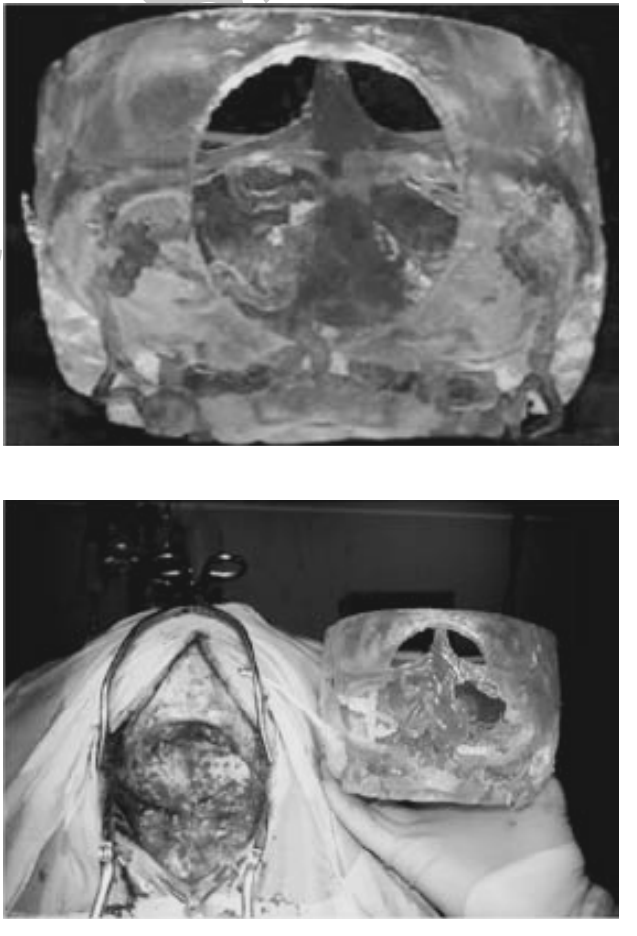

Fig. 1 Case 1: (Top) biomodel of a mid-line cerebellar AVM; (Bottom) sterilized biomodel being used intraoperatively [3], [4], [22]

3 SAMPLE CASE STUDY

Case 1

A 25-year-old man is presented with a subarachnoid haemorrhage [3], [4], [22]. The relevant CT scan revealed a cerebellar Arterio-Venous Malfunction (AVM). Subsequent angiography revealed a complex AVM with multiple flow-related aneurysms on its feeding arteries. It was found out that surgical excision of the AVM was the safest option. A biomodel was requested to assist the surgical planning. A helical CT angiogram was performed and the data were prepared using Anatomics and BioBuild softwares. StereoCol resin was used to allow selective colouration of the vascular structures.

During the operation, the biomodel accurately replicated the AVM. The complexity of the abnormality could easily be appreciated in Fig. 1. The biomodel was used in conjunction with the preoperative angiogram to plan the surgical approach and the selective obliteration of the feeding vessels to the AVM. During the operation, the biomodel was invaluable in assisting with surgical navigation and in verifying the location of various vessels supplying the AVM. The Patient was fully recovered and cured of the AVM due to the post–operation cares.

Case 2

A 53-year-old man is presented with seizures caused by a known recurrent Parafalcine Meningioma [23]. Surgery had been performed on three separate occasions, but unfortunately the tumour recurred. A large part of the skull had been resected and tumour was invading the edges of the cranial deficit as well as the soft tissues and brain. CT scan was performed and biomodel was manufactured using Anatomics and BioBuild softwares.

A custom Acrylic implant was then manufactured to reconstruct the defect (Fig. 2). A custom resection template was also manufactured to allow the surgeon to mark the resection line on the patient's skull. At surgery, the patient's scalp was carefully dissected from the tumour and the skull. The resection template was then contour matched to the skull and resection margin marked. The tumour mass was then resected from the skull and carefully from the brain. The skull was then reconstructed using the custom implant and then the patient made a satisfactory recovery.

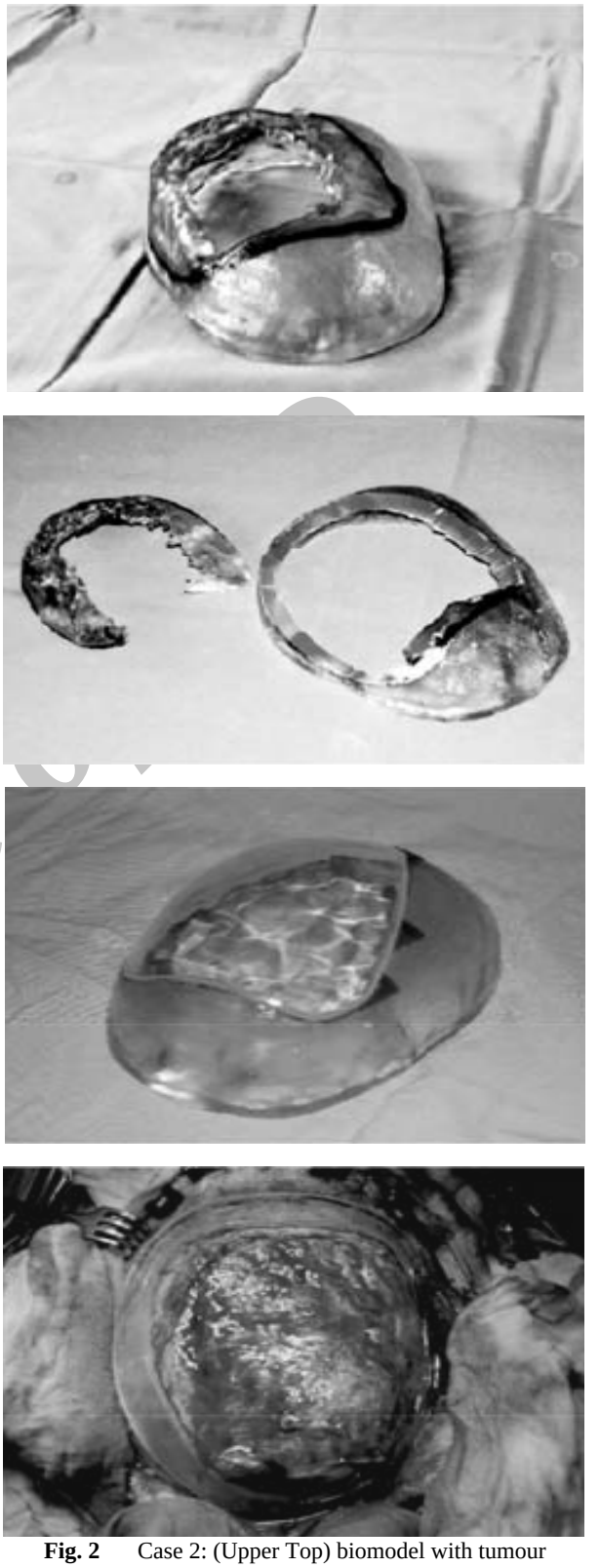

Fig. 2 Case 2: (Upper Top) biomodel with tumour invading the skull. Resection margin marked; (Top) biomodel with simulated tumour resection; (Middle) biomodel with custom cranioplastic implant, (Bottom) resection template fitted to patient intraoperatively [23]

Case 3

A 64-year-old patient is presented with severe low back and leg pain [24]. Previous surgery of lumbar disc prolapse made the patient worse. The patient's imaging revealed a complex lumbar spinal disorder with damaged facet joints at lumbar L4/5 and nerve compression. CT scan was performed and a biomodel was manufactured as shown in Fig. 3. The surgeon used the biomodel to simulate the placement of pedicle screw using trajectory pins and a standard power drill.

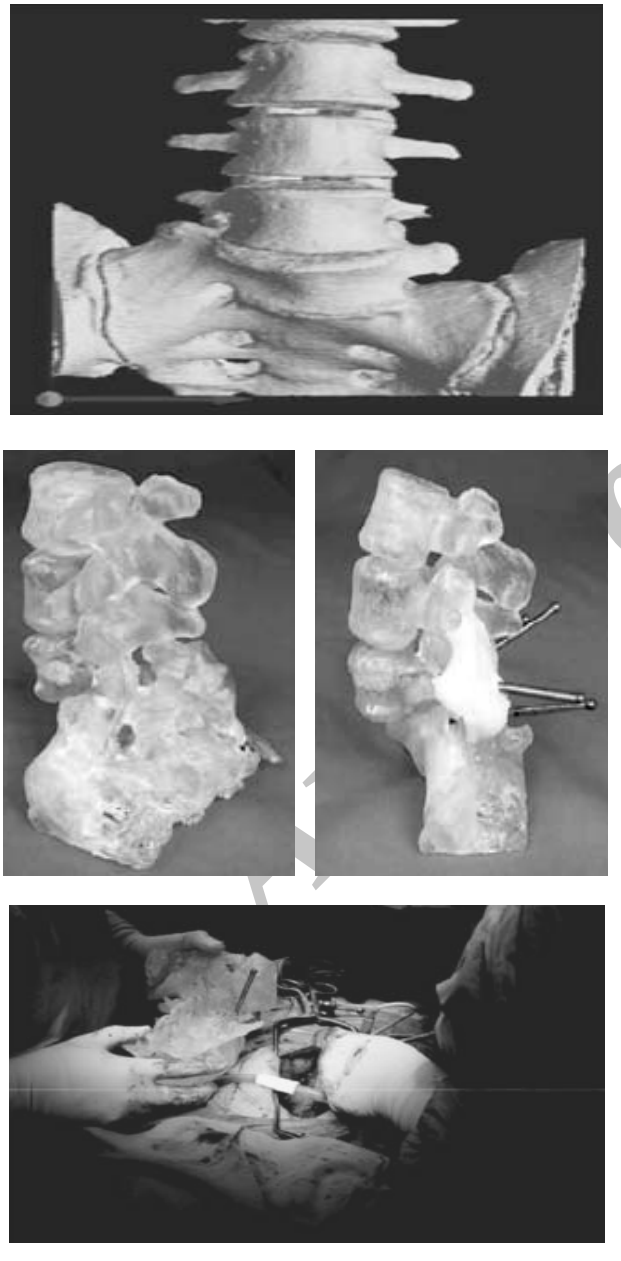

Fig. 3 Case 3: (Left Top) BioBuild model of spine at L4/5; (Left Bottom) biomodel of lumbar spine; (Top) biomodel with stereotactic guide pins and custom templates; (Bottom) sterilized biomodel being used intraoperatively [24]

With the trajectory pins, cold-cure bone cement was shaped to create drill guide templates. At surgery, the biomodel was used to navigate and expose the spine while avoiding neural tissue. The drill templates were then contour matched to the spine and used to drill the pedicles L4/5. The nerves were decompressed and the spine was brought into alignment. The screws were then used to fix two plates to L4/5 to stabilize the level. Bone graft was harvested and packed around the plates to achieve bony fusion.

4 RAPID PROTOTYPING IN MEDICAL APPLICATION

Model layering is the basic factor in all of the purposed RP procedures. Proportional to the materials used in each procedures, specific method for model's layering is utilized from laser photo polymerization of photo sensitive polymers, laser sintering of metal's powders, glue injection to solid integration by exerting pressure and temperature and laser cutting [25], [26]. A common RP procedure can be briefly considered as:

1- Computer 3D modelling.
2- Forming data exchange file (usually in Standard Triangulation Language (STL) format, since this format completely covers the model by triangular elements).
3- Model layering (usually done by the interface software in the specified RP system).
4- Model supporting (usually done by the interface software in the RP system).
5- Manufacturing.
6- Post finishing, post curing, stress relief or electric discharging (especially for medical implant for improving the part's strength to body's reaction).

Combination of medical imaging techniques (e.g. CT and MRI) with CAD and RP technologies has caused significant advances in medical and surgery applications. Physical models provide a proper and exact view of diagnosing for surgeons and implant designers.

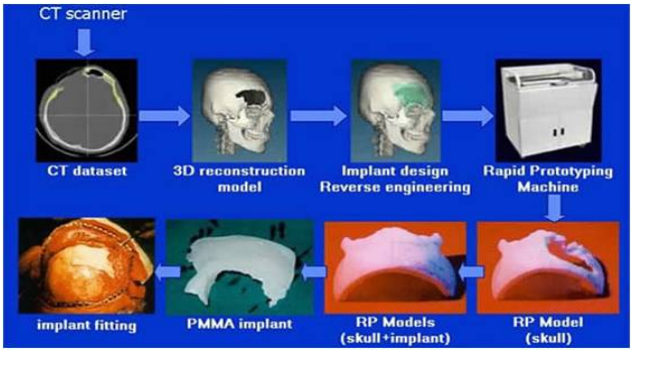

Fig. 4 A complete cycle of medical rapid prototyping [25]

An accurate RP model facilitates correct operation planning and selecting proper implants that a surgeon can practice and examine all the conditions and situations, before real situation. Rahmati et al. have briefly shown a complete medical RP cycle in Fig. 4 [25].

5 THIS STUDY

As mentioned before, performance of common biomodelling softwares is based on the interpreting and image processing of CT or MRI images that in turn necessitates the need of anatomical background for utilizing those kinds of images. In this study, Karbaschi et al. utilized the CATIA cloud point concept for modelling of the human's hard tissue like musculoskeletal system [27]. The implemented technique for biomodelling of a sample femur bone is summarized as below:

1- Sample selection

In this phase, a reasonable and suitable sample of desired tissue without any external destruction is selected. It must be kept in mind that proper condition of the sample's external surfaces is vital for the final model's quality.

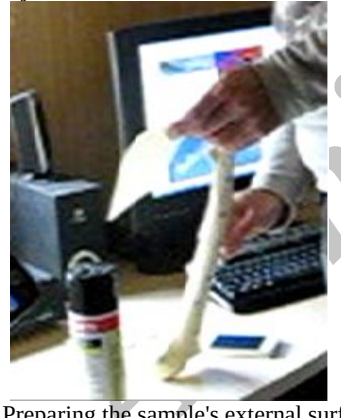

Fig. 5 Preparing the sample's external surfaces [27]

Fig. 6 Optical measurement of femur bone [27]

2- Sample external surfaces preparation

In this phase, sample's external surfaces are prepared for optical measuring purpose. Spraying a special neutral dye on the surfaces (in order to eliminate the reflection glare from the surfaces) and index mark sticking are common activities in this phase (Fig. 5).

3- Optical measuring

Prepared sample will be photographed by special camera from different viewpoints (Fig. 6). Merging and aligning photos, removing the index markers and producing the final cloud point file are common activities in this step.

4- Importing the cloud point file in CATIA

As the output file can't be directly used by the software, first the cloud point file must be imported to the Digitized Shape Editor (DSE) environment. The situation is shown in Fig. 7.

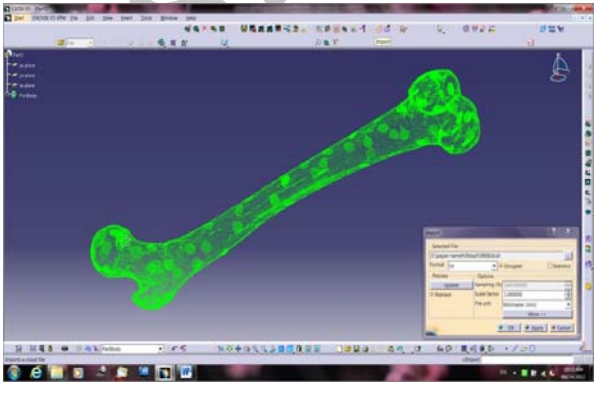

Fig. 7 Cloud points in software's DSE environment [27]

5- Mesh generation from cloud points, checking and correction

At this step, a mesh will be generated to have an imagination about the final volume (Figs. 8 and 9). This step is necessary to check the volume and fix all the possible problems like voids and discontinuities in the final model.

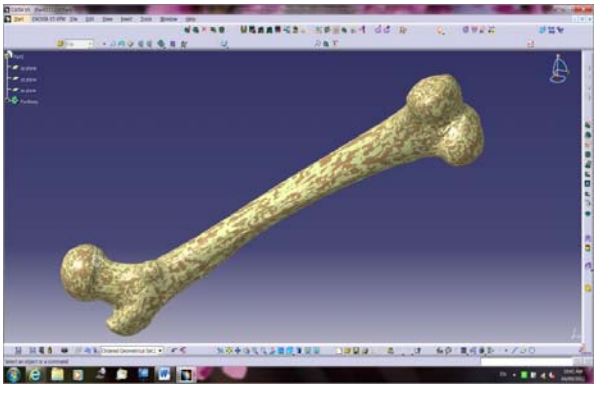

Fig. 8 Mesh generation from cloud points [27]

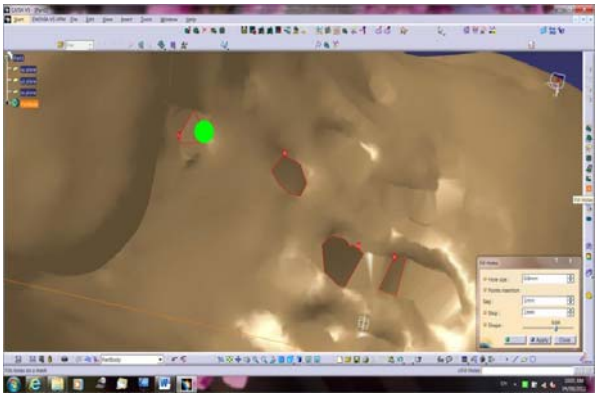

Fig. 9 Mesh checking and correction [27]

6- Volume decomposition, generating main contours, constructing individual solid volumes and final integration

As RP systems can just work with solid models, volume decomposition from the existing mesh in order to generate the key contours (needed for constructing the solid volume) is vital. All segments will then be merged together in order to make the final solid. Contour generation of femur's head and neck, metaphysis and diaphysis sections and sub-volumes merging to construct the final model is shown in figures 10 to 12.

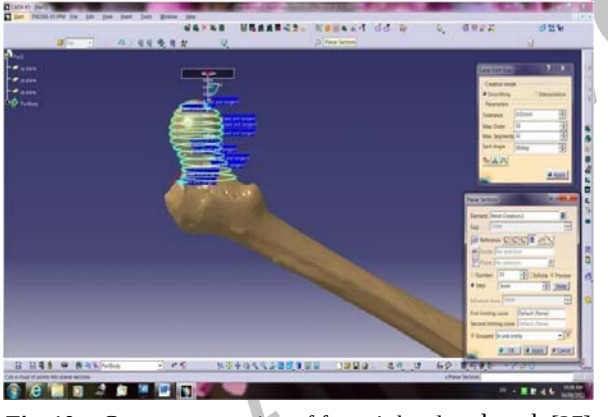

Fig. 10 Contour generation of femur's head and neck [27]

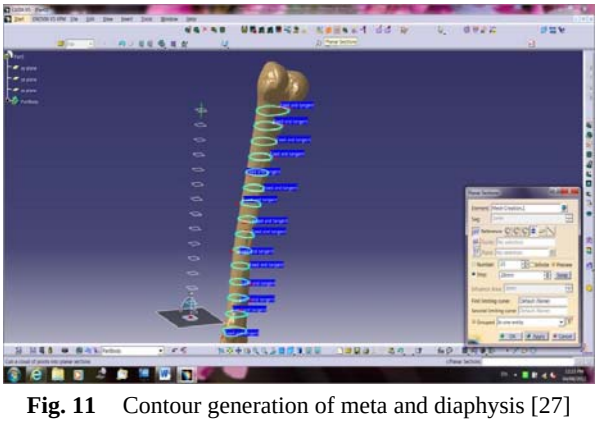

Fig. 11 Contour generation of meta and diaphysis [27]

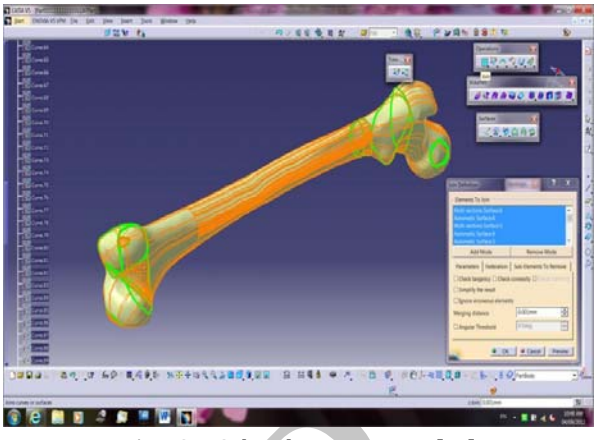

Fig. 12 Sub-volumes merging [27]

7- Final checking and output file generating for RP system

When final solid model is generated, it is ready to be transferred to a RP system via a suitable data exchange format. Since Fused Deposition Modelling (FDM) method is used as RP technique in this study, the output file was generated in STP format.

8- Importing in RP system's software and manufacturing

Each RP system has its own software for converting the imported solid model into layers. These softwares are so powerful that can perform complementary actions such as part's automatic support and relevant affairs. The AURORA RP software of the selected RP system has calculated the following items for manufacturing of this study's sample as:

- Layer thickness: 0.2mm
- Total layers: 209
- Manufacturing estimated time: 3hr, 32', 45"
- Operating temperature: 50.8C
- Total weight: 44.5gr (made from ABS material with approximate length of 25cm)

Supporting for the model was automatically calculated by the software. The manufacturing steps are shown in figures 13 to 15.

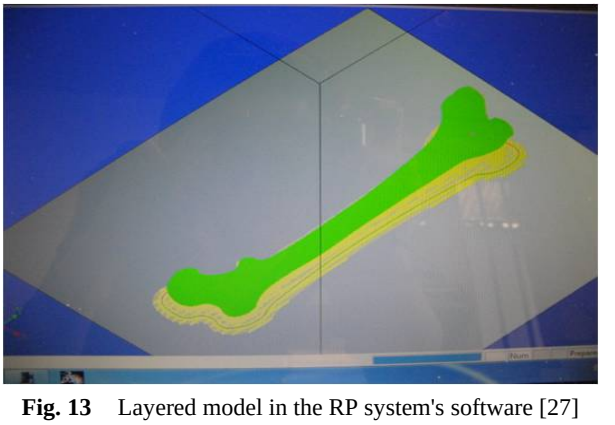

Fig. 13 Layered model in the RP system's software [27]

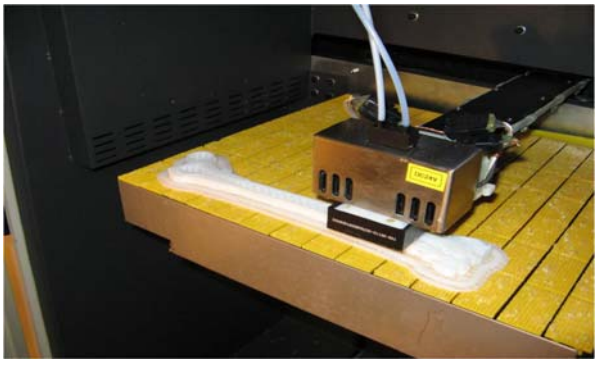

Fig. 14 Manufacturing in progress (1) [27]

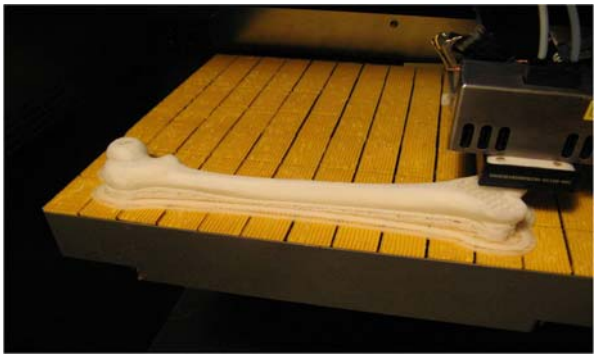

Fig. 15 Manufacturing in progress (2) [27]

Fig. 16 Part's separation from its support [27]

Fig. 17 Completed part with finished surfaces [27]

9- Part's separation from support and surface finishing

When manufacturing process is finished, the part is ready to be separated from its support. After separation, a suitable surface finishing method like smooth grinding will finalize the process. Relevant steps are shown as figures 16 and 17.

6 CONCLUSION

Performance of the current bio modelling softwares is mainly based on image processing algorithms. By the advent of those algorithms, the relevant softwares have been upgraded in turn. Using general modelling software like CATIA is a new challenge in medical applications and biomodelling of human's various organs and tissues. As discussed in the previous sections, photo imaging technique and cloud point concept have been utilized to biomodel a hard tissues like femur bone that has its own special complexity. Comparing the new proposed method in this study with the other common methods has shown the following advantages:

- Software's significant abilities in 3D modelling of complicated volumes and improving the final model.
- Software's simplicity, accessibility, a powerful graphic zone and integrated modules.
- Less requirements for medical knowledge and background to interpret the CT or MRI images.
- Data reduction for modelling which reduces the side costs in comparison to traditional methods.
- Less requirements for special and costly softwares needed for image processing and modelling.
- Reduction of data missing risks while processing the CT images that has direct effect on the quality and precision of the final model.
- Utilization of powerful optical measuring apparatus and providing the possibility for direct production of the final cloud point file.
- Controlling of sections needed for constructing the contours for the final volume. It must be mentioned that the number of sections and layers directly affects the quality and accuracy of final model and manufactured part. Now the proposed optimized slice thickness for CT images is 0.1mm that increases the acquisition time and ray dose radiated to the patient.
- Establishing the RV concept and simulation of manufacturing process, and implementing necessary modification.
- Possibility of performing engineering calculations like Finite Element Analysis (FEA) within the

software and checking the parts performance under the actual conditions.
- Facility of data exchanging among CATIA and other RP systems by producing various data exchange formats.
- Possibility of utilizing the vast material spectrum for manufacturing the final part, because of the software's ability to communicate with various RP systems.
- Possibility of modelling and manufacturing special prostheses (also with specific performances) like dental implants with high quality and low cost.

In spite of the new method's advantages that were listed above, it must be kept in mind that the new method has some disadvantages in some areas like:
- In-vitro capability of tissue modelling. On the contrary, traditional softwares can model the in-vivo parts via CT images, without any need for taking out the specified organ.
- Weak capability of soft tissues' modelling like vessels and nerves.

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