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ORIGINAL ARTICLE

Ying Tie · Ruyu Ma · Ming Ye · Dongmei Wang · Chengtao Wang

Rapid prototyping fabrication and finite element evaluation of the three-dimensional medical pelvic model

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Abstract This paper presents a non-uniform, periodic closed B-spline approximation algorithm for the fabrication of a medical pelvic model, based on rapid prototyping, and also gives the finite element evaluation of the pelvic model. Rapid prototyping (RP), when used in fabricating medical prosthesis, has a strict requirement for closeness and impermeability of STL files. Incorrect data structure in STL files will cause the subsequent slicing process not to proceed. The non-uniform periodic closed B-spline curve approximation method was applied to processing CT data. The precision and size of STL files was improved to optimize the RP model of the pelvis. Finally, the model of the pelvis was evaluated with the finite element method. Results suggest that a high similarity has been achieved in terms of shape, size and biomechanical properties of the pelvic model and the normal one, which validates our argument that rapid prototyping with non-uniform, periodic closed B-spline algorithm is suitable for the fabrication of a pelvic model, which will prove to be significant in the design of pelvic prostheses.

Keywords B-spline curve approximation method · Finite element analysis · Pelvis prosthesis · Periodic closed · Rapid prototyping (RP) · Three-dimensional medical pelvic model

1 Introdution

The traditional surgical resection of a pelvic malignant tumour results in the disability of the patient's lower limbs. In recent years, pelvis replacement [1–3] is adopted successfully in clinical surgery after the resection. The pelvis replacement substitutes individual pelvic prosthesis for the abnormal pelvis, which can save the lower limbs of the patient. Pelvic prostheses can be customized based on the rapid prototyping, and therefore can completely meet the surgical requirements of shape and precision. To achieve ideal shape, precision and function, it is best to avoid modifying the prosthesis during surgery. In customizing the pelvic prosthesis by rapid prototyping, surgery time is reduced, and more importantly, the patient's post-surgery lifestyle is ameliorated.

Rapid prototyping (RP) is widely applied in instances of medical three-dimensional modeling [4, 5]. The RP model of a pelvis can provide the visual and tactual information for diagnosis and therapy, and can assist a surgeon in setting down the surgical plan rapidly. Moreover, the three-dimensional model can be implanted into human body. The graphical mirror function makes the fabrication of the defective part easy, and is designed according to the symmetrical part.

The pelvis is made up of sacrum, coccyx, hipbone, and the substance among them. Through the interaction of the acetabulum and femoral head, the pelvis has a role in supporting the weight of the upper half body and transferring the weight to the lower limbs. Furthermore, the pelvis protects the organs in the pelvis. Due to the complexity of the structure, the three-dimensional modeling of pelvis is rather difficult.

In this paper, a novel method of fabricating and evaluating a human pelvic model is studied. We applied a non-uniform, periodic closed B-spline approximation algorithm to process CT data. Then, the correct and concise STL files were obtained for the fabrication of a pelvic prosthesis based on rapid prototyping. Moreover, the three-dimensional finite element analysis method was also applied to evaluate the biomechanical properties of the pelvic model.

2 STL file

An STL format file is the conversion standard of data between the CAD entity model and the RP machine [6–8]. The process of generating an STL file involves the tessellation of the surface

Y. Tie (✉) · R. Ma · M. Ye · D. Wang · C. Wang
Institute of Life Quality via Mechanical Engineering,
School of Mechanical Engineering,
Shanghai Jiaotong University,
No.1954, HuaShan Road, 200030 Shanghai, China
E-mail: tieying@sjtu.edu.cn, tieying127@163.com
Tel.: +86-21-62932905
Fax: +86-21-52541413

and triangulation, which generates a large number of triangular patches to approximate the CAD entity model.

If the structure of STL file is incorrect, the slicing process will not carry through after triangulation. In order to generate high-class STL files, there is a strict requirement not only for the closeness and impermeability of STL files, but also for CAD original data. Current RP processes rely primarily on CAD representation. If the CAD model has defects, such as a large amount of undesirable gaps, degenerate facets and flipped normal, then time-consuming processes to repair the facets are required. Moreover, when a higher resolution is required, the faceting time becomes longer and a much larger STL file is generated, which may cause storage and computing problems.

3 Preprocessing of CT data

After the CT data is converted into standard DICOM format files, image recognition software is used to extract the outline curve of the pelvis by means of grey-level recognition. The outline curve obtained by this means may produce zigzag, so it needs to be rounded according to curvature rule (so that the outline curve has no discontinuity). During the process of rounding, the parts of section outline curve which have anatomical features should be preserved, and the other parts should be smoothed as much as possible in order to generate results that can be used for remodelling.

4 Periodic closed B-spline curve approximation method

4.1 Curve uniformity

In order to assure the accuracy of the STL files, all the curves should be uniform: both in the number of controlled nodes in all curves, and in the location of the initial node. This makes the generated surface continuous, which can reduce the incorrect information of triangular patches in accord with STL file format requirements [9].

4.2 Advantage of the non-uniform periodic closed B-spline curve approximation method

The advantages adopted the non-uniform, periodic closed B-spline curve are:

1. The locality of B-spline curve is used to suppress the impact of noise points on the entire outline curve, thus making the curve smoother.
2. The centripetal parameterization method is applied to the parameterization of data nodes in the curves with large curvature [10] efficiently. The outline curve of the object tissue is closed, so the periodic closed B-spline curve is used to approximate outline curves, thus reducing the amount of the data and making the outline curve more compact.
3. The final results can be written into IGES format files, which make it easy to exchange data among various CAD/CAM software.

4.3 Parameterization and the structure of the node vector

The centripetal parameterization method is applied to the parameterization of data nodes of the outline curves. $\bar{u}_i$ is defined as the parameter corresponding to the data nodes of the outline curves , the number of which amounts to $m+1$; considering the quality of the close curves ($Q_{m+1} = Q_0$), the parameter $\bar{u}_{m+1} = 1$ is added. Other parameters are defined as follows:

$$d = \sum_{k=1}^{m+1} \sqrt{\left|Q_{kMOD(m+1)} - Q_{k-1}\right|} \quad \bar{u}_0 = 0, \tag{1}$$

$$\bar{u}_k = \bar{u}_{k-1} + \frac{\sqrt{|Q_k - Q_{k-1}|}}{d} \quad k = 1, 2, \cdots, m \tag{2}$$

Suppose that the control polygon is constituted by $n+1$ mutual difference vertices $\{P_0, P_1, \cdots, P_n\}$, and the corresponding node vectors are $\{u_0, \cdots, u_p = 0, u_{p+1}, \cdots, u_n, u_{n+1}, \cdots, u_{n+p}, u_{n+p+1} = 1, \cdots, u_{n+2p+1}\}$, as shown in Fig. 1.

The function of the curves is given by:

$$C(u) = \sum_{i=0}^{n+p} N_{i,p}(u) P_{iMOD(n+1)} \quad (0 \le u \le 1) \tag{3}$$

4.4 Algorithm

The object function is presented by the squared sum of the distance between nodes ($C(\bar{u}_k)$) corresponding to the parameters $\bar{u}_k (k = 0, 1, \cdots, m)$ on the curve $C(u)$ (approximated), and the corresponding nodes on the outline curves [11, 12].

$$f = \sum_{k=0}^{m} \left|Q_k - C(\bar{u}_k)\right|^2 = \sum_{k=0}^{m} \left|Q_k - \sum_{i=0}^{n+p} N_{i,p}(\bar{u}_k) P_{iMOD(n+1)}\right|^2 \tag{4}$$

The interpolating nodes matrix equation is given by:

$$(M^T M) P = Q \tag{5}$$

Since there is not less than one parameter $\bar{u}_k$ in each node interval of the node vector, $\left(M^T M\right)$ is positive and definite, and can be solved by the Gauss elimination method.

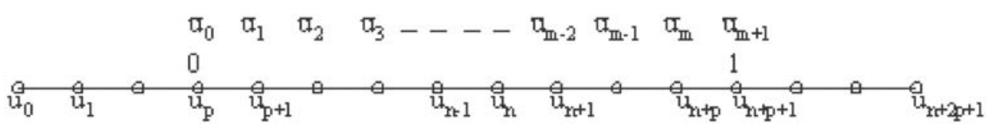

Fig. 1. Node distribution of curve

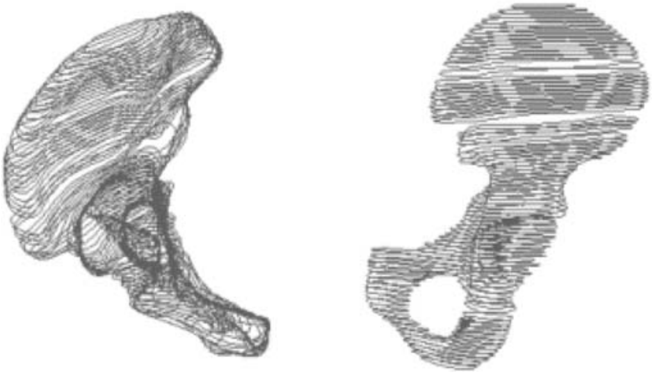

Fig. 2. Control polygon and approximating curves under different control error

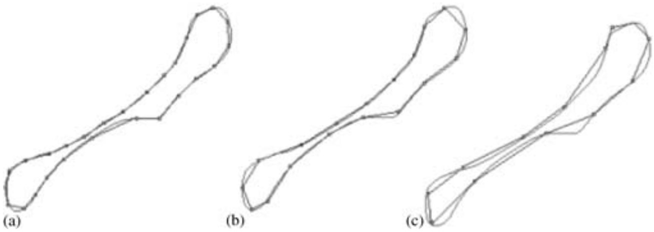

Fig. 3. Wireframe of upper pelvis under different ε

We use a cubic closed B-spline curve ($p = 3$) is C^2 continuity, since it can adequately describe the outline curve.

The length ratio of the outline curve ε is applied to describe the controlling error of a single section, which is considered to be a large change in the outline curve length. The approximated curves under different control error and wireframe conditions of the upper pelvis (when $\varepsilon = 0.005$) are shown in 2 and 3.

The outline curves of the pelvis extracted should include low-density cancellous bone and a thin layer of dense cortical bone, which will have the main role in distinguishing the material characteristics of the cancellous bone and cortical bone in the finite element analysis. The final results are exported in IGES format files to repair the generation of the surface.

4.5 Generation of the curved face

The outline curves are used to estimate the skin surface. In this process, the total amount of surface should be as small as possible to improve the accuracy of the STL files. If branching occurs, it should be skinned separately, and stitched. Since error often occurs in the branch, more attention should be paid to the uniformity of the curve.

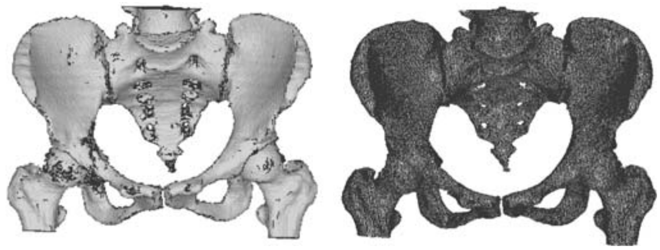

Fig. 4. STL file of the pelvis in surface and triangle format

4.6 Closing of the curved surface

If it is not closed, the curved surface should be mended using the small patches. Then, the whole model is exported in STL format, and converted into the RP system for slicing. The STL file of pelvis (Fig. 4) is opened in surface and triangle format in Magics RP 5.41 software.

5 RP of pelvis

The RP approach includes a group of novel techniques widely used in engineering for the quick fabrication of geometrically complex conceptual and functional solid models. Examples include: computer aided design (CAD), computer aided manufacture (CAM), computer numerical control (CNC), precise servomechanism, and new materials. RP normally begins by creating a solid modeling file to represent the object design, and ends with the building of a 3D physical replica of the object, in layer-by-layer manner. The detail process is as follows: the three-dimensional model of the pelvis is constructed on the PC and sliced; then, the PC controls the materials to be deposited on the operating platform of the RP machine, according to outline curve of the each layer, at an interval of about $0.05 \sim 0.10$ mm. The ultimate three-dimensional product is then formed layer-by-layer. Currently, RP technique includes: stereolithography apparatus (SLA), laminated object manufacturing (LOM), fused deposition modeling (FDM), and so on. In the view of machining accuracy

Fig. 5. The devices of RP

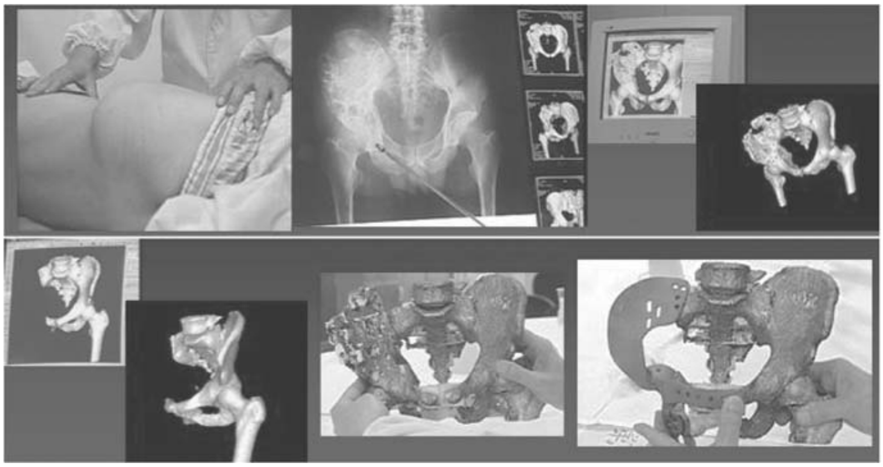

Fig. 6. The fabricating process based on the RP

and manufacturing cost, the LOM system is used in this paper. The processed paper, which is constituted of a paper-based material, coated adhesive and modified additive, is selected as the input material. It has the benefits of being low cost and maintaining a solid phase during the process, thus keeping the extent of warpage small.

The STL files of the pelvis model are imported into the RP system to fabricate the solid entity (see Fig. 5). The RP machine used in this paper was a JingJiJiDian (Shanghai), model type ZSW–1. The RP machine maintained a preset layer thickness of 0.08 mm, and the required time was 8 h. The fabricating process of the pelvis and prosthesis is shown in Fig. 6.

6 Finite element biomechanical evaluation of the pelvic model

Since finite element analysis (FEA) involves high-accuracy, digital software, imported data are subject to special requirements. When the surface generated from Sect. 4.6 is exported into (FEA) software (ANSYS 5.6), some error may be checked by the system, including gap, over-tolerance, and so on. The outline curves of the pelvis in IGES format generated from Sect. 4.4 are imported into ANSYS software. These curves must be relinked and redivided by means of linking and skinning, which are applied to form the outline surface. Then, the entity is formed based on these surfaces. Based on the strong meshing function of ANSYS 5.6, the pelvis is meshed with respect to the volume element of cancellous bone and the membrane element of cortical bone. The material qualities referred to in this study include: an elastic modulus of cortical bone of 13 700 MPa; an elastic modulus of cancellous bone of 1850 MPa; and a Poisson's ratio of 0.3. Myodynamia vectors of muscles, which are related to the movement, are selected. Based on human skeletal and muscle systems, the attachment positions of each muscle are determined and marked. Those places are restrained to prevent the rotation of the model and any rigid movements. The forces are applied to acetabulum according to hip joint statistics in the "two feet standing state" [13].

The finite element model of half the pelvis is shown in Fig. 7. The finite element model of the pelvis is used to study the stress distribution in the standing state (see Fig. 8), and the force transfer on the pelvis. The biomechanical results will provide references to the design of the pelvic prosthesis and improve the life quality of the patient with pelvic disease. The biomechanical results are all consistent with those of the previous experimental

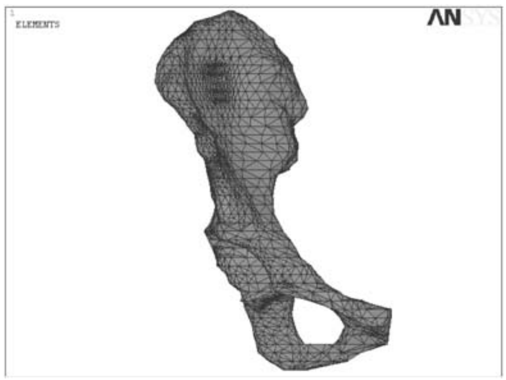

Fig. 7. Finite element solid model of the pelvis

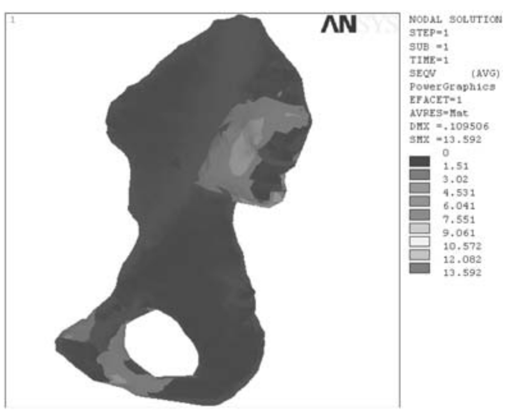

Fig. 8. Stress distribution on pelvis

research [14–17]. Therefore, the pelvic model and pelvic prosthesis fabricated based on method of this paper is suitable for clinical application.

7 Conclusion

We designed a pelvic prosthesis using a rapid prototyping technique based on a non-uniform, periodic closed B-spline algorithm. With this approach, the amount of original data is reduced and the outline curve become more compact, which in turn reduces the errors of the triangular patches in the generation of STL files. The STL files generated with this method results in the fabrication of a high-class entity model. The biomechanical evaluation of finite element-based model provides reference to the design of the prosthesis. We conclude that our design will improve the life quality of patients with pelvic disease.

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