Computer-assisted design of individualized femoral prosthesis according to 3D reconstruction of CT images***☆

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Abstract

BACKGROUND: Due to individual characteristics of human body, it is difficult to well match between standard prosthesis and patient skeleton. Computer-assisted design and manufacture of individualized prosthesis can effectively prolong artificial joint lifespan and quality and reduce revision rate. However, related studies are few in China.

OBJECTIVE: To explore computer-assisted design for individualized femoral head prosthesis according to three-dimensional (3D) reconstruction of CT images for improving prosthesis and affected skeleton matching.

METHODS: The CT scanning image of one healthy male volunteer, with no hip joint disease, was used. His femur was scanned with GE Speed Light CT with 3.0 mm thick cross-section slices. CT 2D images were transmitted to a computer. The medical image format was translated from DICOM into bmp. Inner and external bone contours were drawn automatically or by hand and processed digitally, and then these data were downloaded into 3D Mimics8.1, and Rapidform2004 software. The 3D femoral canal model was rendered. Femur canal contours curve was downloaded into the Solidworks2004 software in the form of dxf. Femoral prosthesis was designed on the base of femoral canal contours curve.

RESULTS AND CONCLUSION: The CT image was transmitted in the form of vector by a set of self-made medical image processing software. The accurate 3D femoral internal/external outline model was obtained by CT 2D image and reverse technique. Suitable femoral prosthesis was designed by means of image reverse engineering and norientation CAD. Reverse engineering and CAD provide an effective way to develop individualized prosthesis, improve the matching of prosthesis and affected skeleton, prevent prosthesis loosening and improve long-term stability.

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INTRODUCTION

Hip replacement is hopeful for patients with severe hip joint disease. However, matching degree between artificial joint and medullary canal of upper femur directly influences long-term stability, range of motion, and artificial joint biomechanics. Well matching can obtain early stability and lay a foundation for long-term stability. Due to individual characteristics of human body, it is difficult to well match between standard prosthesis and patient skeleton. In addition, some patients with skeleton congenital malformation or large area damage due to skeleton diseases, resulting in different skeleton from normal condition, cannot be treated with standard prosthesis. Computer-assisted design for individualized femoral head prosthesis was used to develop individualized prosthesis according to each patient, which improved the matching of prosthesis and affected skeleton, prevent prosthesis loosening and improve long-term stability[1-3].

SUBJECTS AND METHODS

Design: Observation experiment.

Time and setting: The experiment was performed at the Laboratory of Department of Orthopedics, Affiliated Hospital of Nantong University and CAD&CAM Laboratory of Mechanical Engineering College of Nantong University from September 2005 to August 2007.

Subject

A healthy male volunteer, aged 30 years, 175 cm high and 65 kg weight, free of hip disease, was selected for CT scanning. The experiment was approved by Hospital Ethics Committee, and informed consent was obtained from the subject.

Methods

CT image data acquisition

The subject lay on the back at the center of GE Speed Light 16-slice spiral CT bed, and both lower limbs were placed in rotation neutral position, with CT focal length center at hip joint. Scanning condition was as follows: 120 kV, 100 mA, slice thickness 3 mm, scanning time 1 second, matrix 512×512, pixel depth 16 bit, window diameter 360 mm, window width 1 800, window level 600. The scanning involved up-middle femur, 1 cm superior femoral head and 3 mm interval. The DICOM CT image data were stored, transferred to CT three-dimensional reconstruction work platform, and downloaded to mobile hard drive. The data were transferred to minicomputer working platform.

CT image reduction

CT image data of DICOM format cannot be recognized in vectorization; therefore, the medical image format was translated from DICOM into bmp. According to DICOM3.0 standard, self-made dicom to bmp 1.0 software was used to translate the format from DICOM into bmp. DICOM document is composed of file header plus data segment. The file header was removed, and data segment was obtained, and bmp image was generated according bmp file format.

Bitmap compile pretreatment and femoral contour extraction

According to proximal femoral anatomic features, automatic and manual extractions were used[4]. Stem of femur was extracted automatically using mimics system, and lesser trochanter and the above areas were extracted manually. The extractions were treated using photoshop paintbrush software.

Reverse reconstruction of femoral model

Mimics8.1 reverse engineering software (materialize, Belgium) was used for femoral data denoising and slice image data integration to complete primary contour three-dimensional reconstruction and obtain contour characteristics, followed by translation of standard three-dimensional document format STL required by rapid prototyping system[5-6]. Rapidform2004 reverse engineering software (INUS, South Korea) was used for contour correction and final building to complete femoral three-dimensional reconstruction. Inner and external bone contours were drawn by Rapidform2004 sections, and femur canal contours curve was downloaded into the Solidworks2004 software in the form of dxf for computer aided design (CAD).

Individualized femoral prosthesis design

In Solidworks2004 software, individualized prosthesis three-dimensional model was established based on femur canal contours. Briefly, the original femur canal inner surface model section contour was modified to produce prosthesis model section contour; three-dimensional surface was generated, and in each section contour, spline curve comprised 12 points, for a total of 14 contours. The distal prosthesis was polished to reduce stress shielding; the proximal prosthesis neck and femoral head were designed to form prosthesis three-dimensional solid model.

Main outcome measures: Femoral inner and external bone contours three-dimensional solid models.

Design, enforcement and evaluation: The experiment was designed and performed by Zhu Jian-wei and evaluated by other authors with a blind method.

RESULTS

The CT image was transmitted in the form of vector by a set of self-made medical image processing software, dicom to bmp 1.0. Cross-section of medullary cavity below femoral lesser trochanter was round or oval-like shaped; cortical bone gray scale was significantly different from medullary cavity, with clear margin and continuous curves (Figure 1).

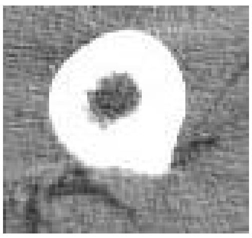

Figure 1 Marrow cavity in the lower lesser trochanter drawn automatically

Femoral proximal lesser trochanter and above medullary cavity was mainly cancellous bone, with irregular cross section appearance and uneven gray scale (Figure 2).

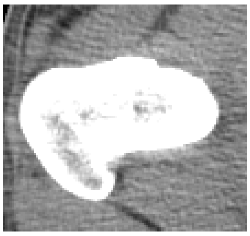

Figure 2 Irregular transverse traction of marrow cavity in the lower lesser trochanter

Complete contour curves were obtained by manual operation in combination with computer automatic recognition, in particular contour of femoral medullary cavity was extracted manually according to anatomy (Figure 3).

Figure 3 Lesser trochanter and upper part drawn by hand

The accurate 3D femoral internal/external outline model was obtained by CT 2D image and reverse technique (Figure 4). Lateral view of reconstructed femoral upper medullary cavity was S shaped, and the upper part was wide, but the lower part was narrow, like a funnel (Figure 5).

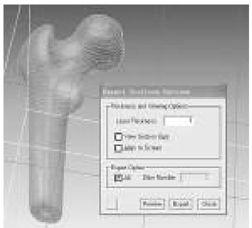

Figure 4 3D femoral internal/external outline model

Figure 5 Lateral view of the reconstruction of upside femoral cavity

Suitable femoral prosthesis was designed by means of image reverse engineering and norientation CAD with prosthesis stem model lesser than cross section medullary cavity contour; following proximal and distal processing, a well matching prosthesis stem was generated, which could be successfully inserted into the medullary cavity (Figure 6).

Figure 6 Model of femoral cavity implanted with femoral prosthesis stem

DISCUSSION

CT and MR image work station in hospital frequently utilize volume reconstruction method, which only serves as three-dimensional display, but not be used for further engineering processing, thereby limiting application of human organ imaging information in biomedical engineering. CT data general file is DICOM data format[7-9]. CT image processing is at an advanced level in GE, USA, Siemens, Germany, and Toshiba, Japan, which have developed CT system with three-dimensional reconstruction. However, the application is greatly limited due to high cost, over 100 000 $ due to technical monopol, application in specific imaging system alone, but not in common computer. Moreover, the data cannot be output or shared. In addition, the image format translation is very difficult because of different image data format and secrete or enciphering file code[10]. Due to these conditions limitation, current CT images are collected using scanner followed by digitization. Hospital medical imaging apparatus can output examination results by a form of film, and the film is scanned using high resolution scanner into general bitmap document to transform into data that can be processed by computer. However, original images following several photoelectric transformation have various noises, and scanning apparatus directly affects quality of scanning data and influences accuracy of subsequent image processing. Therefore, the present study transferred DICOM CT image data from mainframe to work platform of CT three-dimensional reconstruction, transferred into mobile hard drive through USB port of image repository and downloaded to mini-computer work platform for later processing. This method prevents errors of CT images produced by scanner. Moreover, self-made image format transition software dicom to bmp 1.0 was used to translate DICOM format into BMP bitmap. The resolution of CT data at DICOM format is 512×512×256, and that of BMP format remained 512×512×256. Therefore, bone contour information remained complete. This software has characteristics of high accuracy, rapid speed, and applicable usage in common CT and MR images.

Although many image processing software posses contour processing function, most systems are not professional for a large amount of point data, therefore, take a lot of time in simplify point data and contour reconstruction. Therefore, to effectively shorten time to simplify point data and contour reconstruction is important in improving image processing systems[11]. In addition, image reverse engineering and norientation CAD were utilized here, which reserved advantages of reverse engineering and utilized solid and contour model establishment functions of CAD software. This combination is a good method in RE/CAD technique in medical field. Because it meets requirements of diversity, complexity and speedability of artificial joint, and can be used in custom-made of artificial pelvis, vertebral body and other joint implants[12], as well as in three-dimensional finite element analysis[13-16].

Three-dimensional reconstruction of femoral medullary cavity showed that the calcar femorale in posterior medial proximal femur protrudes towards medullary cavity, divides the medullary cavity into two parts, reduces inner diameter of anterior and posterior medullary cavity; the larger part at the anterior medullary cavity is useful for prosthesis design and called effective medullary cavity. Favorable support after femoral prosthesis implantation can prevent prosthesis micromovement due to torque and subsidence. Prosthesis stem can pass through the effective medullary cavity alone, therefore, three-dimensional appearance is the most important evidence for stem design. Calcar femorale is a compact bone plate and plays an essential role in prosthesis stability and force transduction. Therefore, medullary cavity expansion direction and prevention of calcar femorale injury benefit long-term effect of cementless prosthesis.

Prosthesis aseptic loosening is a major factor that influences artificial joint lifespan and patient quality of life. Mechanical and biological factors are main factors inducing aseptic loosening. The present study increased prosthesis and bone matching to reduce micromovement and retionalise stress distribution. Tight matching of prosthesis and bone can increase prosthesis early stability and stimulate biologically fixed bone ingrowth to reduce biological factors-induced loosening and improve patient quality of life and prosthesis lifespan. Studies reported that after CAD individualized prosthesis implantation, the bone density around the prosthesis was greater than other prostheses and displayed better clinical outcomes[17]. Although manufacture methods of CAD individualized prosthesis are different, the basic principles are common, *i.e.* accurate matching of prosthesis and medullary cavity. In artificial hip replacement, the matching degree of prosthesis and femur is an important factor for long-term effect. Optimal artificial joint design mainly involves optimization of joint stress distribution, which depends on optimization of joint geometric appearance, improvement of matching degree of prosthesis and femur, as well as prosthesis materials. As obvious anatomic variance of proximal femur[18-19], theoretically, CAD individualized prosthesis is the ideal prosthesis for biological fixation to achieve accurate matching of prosthesis and medullary cavity. Moreover, low elastic modulus materials in combination surface processing technique benefit stress transduction and bone ingrowth, increase long-term stability, and prolong femoral prosthesis lifespan[20].

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基于 CT 三维重建个体化股骨假体的计算机辅助设计***☆

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摘要

背景：由于人体的绝对个性化特点，标准人工假体与患者骨骼之间的误差使二者难以很好匹配。计算机辅助设计和制造个体化假体克服了其他假体的缺点，可有效地延长人工关节的使用寿命和使用质量，并可能解决人工关节的翻修问题。国内的研究尚处于起步阶段。

目的：基于 CT 图像的三维重建，探求个体化股骨假体计算机辅助设计在提高假体与病变骨骼匹配度中的作用。

方法：CT 扫描对象为 1 例健康男性志愿者，排除髋关节疾患。采用 GE Speed Light 16 排螺旋 CT 对股骨中上段进行层厚 3 mm 扫描，得到 CT 数据的二维图像，利用自主开发的数据格式转换软件将 CT 图像转换为 bmp 格式。对位图编辑预处理，用 Mimics8.1 软件进行矢量化处理，提取股骨内外轮廓。然后输入 Mimics8.1 和 Rapidform2004 三维反求工程软件中，生成股骨内外轮廓的特征曲线，重建股骨三维模型。将股骨髓腔的特征轮廓曲线 dxf 文件输入计算机辅助设计建模软件 Solidworks2004 中，以此股骨髓腔轮廓为基础，完成个体化股骨假体的设计。

结果与结论：利用自主开发的数据格式转换软件，实现了 CT 图像信息的矢量转换。以 CT 二维图像为依据，进行三维反求，可获得精确的股骨内外轮廓三维实体模型。采用反求工程与正向计算机辅助设计相结合，可设计出匹配良好的个体化股骨假体。提示反求工程和计算机辅助设计技术为个体化假体的研制提供了一个有效可行的途径，解决假体与病变骨骼的良好匹配，可防止假体松动，提高其长期稳定性。

关键词：股骨；三维重建；计算机辅助设计；个体化假体；人工假体；假体松动；假体稳定性
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课题的创新点：自主研发一套数据格式转换软件系统，对医学图像信息的转换简便易行；采用图像反求工程和正向 CAD 设计相结合的方法，设计个体化假体。

提供临床借鉴的价值：以 CT 二维图像为依据，进行三维反求，可获得精确的股骨内外轮廓三维实体模型；采用图像反求工程和正向 CAD 设计相结合的方法，设计出个体化股骨假体，可以有效减少和防止骨吸收和无菌性松动的发生，这对于其他人体器官的三维模型建立同样具有很好的借鉴作用。