Automated Preoperative Planning of Femoral Component for Total Hip Arthroplasty (THA) from 3D CT Images

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Abstract. This paper describes a method for 3D automated preoperative planning of the femoral stem in total hip arthroplasty (THA). The stem planning is formulated as a problem to determine the optimal position, rotation, and size, on the 3D surface model of femur reconstructed from CT images. We obtain the parameters that maximize the fitness between the femoral canal and stem surfaces subject to the positional and rotational constraints. The maximization is performed by local optimization from multiple initial positions. The proposed method was experimentally evaluated by the difference from planning results of an experienced surgeon in 7 cases. The average positional and rotational differences were 1.9 mm and 2.5 deg., respectively, and there was size difference only in 1 case for the proposed method while these differences were 2.8 mm, 5.0 deg., and 5 cases for an existing method. The proposed method showed better performance than the existing method.

Keywords: computer assisted surgery, stem fitness, anteversion angle, orthopaedic implant.

1 Introduction

Recently, surgical navigation and robotic systems have been developed for total hip arthroplasty (THA) for the purpose of accurate placement of the orthopaedic implants in preoperatively determined 3D position and orientation [1-3]. This fact means that preoperative planning is becoming important because the preoperative plan can be accurately executed using these systems. In preoperative planning of THA, anatomical compatibility of each implant component with host bone is essential for stable fixation and good clinical results. Especially, the fit and fill of the cementless femoral component (stem) in the femoral canal are important factors for component stability [4-6]. Recently, CT-based interactive systems for preoperative 3D planning have been developed in order to quantitatively visualize the fit and fill [7]. However the interactive 3D planning is subjective as well as involves time-consuming, which limit its clinical use.
In order to solve these problems, we have been developing the automated preoperative planning system for THA, which automatically select optimal size, position, and orientation of the stem.

In our previous work, we have defined the objective function which describes the “fitness” value of the stem from surgeon’s expertise and his planning results. And we have determined the solution by one-by-one search at the interval of 1.0 mm and 1.0 deg. in each axis [8-9]. However, this procedure of search is not appropriate because there is a possibility that the system overlook the solution which maximizes the fitness. On the other hand, related to our efforts, Viceconti et al. proposed the use of volume registration between the femoral canal and stem [10] for automated placement of the stem. However, image matching criteria used in volume registration were not derived from stem fitness criteria used by the experienced surgeon.

In this study, we propose an automated preoperative planning system of the femoral stem using 3D CT data. We use the definition of the “fitness” which we have used in previous work. In addition, we propose the constraints which describes the surgeon’s expertise of the positional relation of the stem and the femur, and the optimization procedure to maximize the fitness. To evaluate the performance of the proposed system, we apply our method and the existing method [10] to 7 cases, and measure the difference between automated planning results and those of the experienced surgeon.

2 Methods

2.1 Preconditions

Block diagram of proposed system is shown in Fig. 1. As the patient information, we assume that 3D CT image of hip joint of the patient is given. The 3D model of the femoral canal is reconstructed from CT images, and the femoral coordinate system and the anatomical feature points are determined on its 3D models. As the implant information, we assume that the 3D shape models of all the variations in the femoral stems are given. Outputs of this system is the set of parameters \( z = [t, r, s] \), of the position \( t \), orientation \( r \), and size \( s \) of stem.

The femur coordinate system is defined as Fig. 2. In specification of the femur coordinate system, we use the table top plane of the femur and the peak of the lesser trochanter. The \( z \)-axis of femur coordinate system is defined as the canal long axis estimated from the 3D model of femoral canal. The \( x \)-axis is orthogonal to the \( z \)-axis, and parallel to the table top plane. The \( y \)-axis is defined as the axis orthogonal to both \( x \) and \( z \)-axes. The origin is defined as the intersection point between the \( z \)-axis and the line which is perpendicular to the \( z \)-axis and passes through the peak of the lesser trochanter (Fig. 2 sagittal view).

2.2 Definition of Objective Function of Stem Fitness

We formulate the preoperative planning of the stem as the optimization problem that obtain the parameter \( z \) that maximizes the stem fitness evaluate function. The criteria in stem planning are defined as follows: