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Short Communication

Femoral hip prosthesis design for Thais using multi-objective shape optimization

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ABSTRACT

The long-term success of Total Hip Arthroplasty (THA) depends largely on how well the prosthetic components fit the bones. The majority of cemented femoral hip prosthesis failures are due to aseptic loosening, which is possibly caused by cracking of the cement mantle. The strength of cement components is a function of cement mantles having adequate thickness. Since the size and shape of cemented femoral hip prostheses used in Thailand are based on designs for a Caucasian population, they do not properly conform to most Thai patients' physical requirements. For these reasons, prostheses designed specifically for Thai patients must consider the longevity and functionality of both cement and prosthesis. The objective of this study was to discover a new design for femoral hip prostheses which is not only optimal and safe in terms of both cement and prosthesis, but also fits the selected Thai femur. This study used a small-sized Thai femoral model as a reference model for a new design. Biocompatible stainless steel 316L (SS316L) and polymethylmethacrylate (PMMA) were selected as raw materials for the prosthesis and bone cement respectively. A multi-objective shape optimization program, which is an interface between optimization C program named NSGA-II and a finite element program named ANSYS, was used to optimize longevity of femoral hip prostheses by varying shape parameters at assigned cross-sections of the selected geometry. Maximum walking loads of sixty-kilograms were applied to a finite element model for stress and safety calculations. Results show that prosthesis shape is a significant factor in the causes of stress occurring on both the prosthesis and bone cement. Since PMMA is weaker than SS316L, the strength of the cement is more important when selecting solutions for the safety of the prosthesis. The safety factors of the cement and prosthesis of the finalized prosthesis are 1.200 and 1.109 respectively. In conclusion, the new hip prosthesis design is able to resist maximum walking loads of sixty-kilograms while both cement and prosthesis remain safe. The newly designed prosthesis also fits well with chosen small-sized Thai femur.

1. Introduction

Total Hip Arthroplasty (THA) is an effective treatment for osteoarthritis and has been performed on a very large number of patients worldwide. In Thailand, the size and shape of cemented femoral hip prostheses used are based on designs for a Caucasian population. Nevertheless, the results of the morphometric measurements from the Caucasian population are different from the Thai population [1]. In addition, a study by Luangjarmekorn [2] shows that most morphological parameters of Thai femurs are significantly different from those of Korean, French, and American femurs. For Thai patients, the problems of mismatching still remain although the small size of Caucasian based prostheses designs were used [3]. Problems from improper size and shape of femoral stem prostheses were found, for example, incomplete cement mantle might be a cause for early loosening [4,5] and long term complications such as aseptic loosening [6]. For these reasons, a specific design for Thai patients is vital and new design must consider the issues of longevity and functionality.

Effective techniques used for designing femoral hip prostheses include shape optimization and the finite element method. The finite element method (FEM) is a widely used process for analyzing the prosthesis under various types of loading conditions due to difficulties of performing prosthesis tests in vivo.

Several studies have employed FEM to determine the strength of hip prostheses. Bennett and Goswami [7] performed FEM on six hip stem designs. The results of this study show that differences of cross-sections are important factors for stress and displacement of designed stems. Ploeg et al. [8] demonstrated that FEM can be applied with confidence to support standard fatigue testing of hip stems. Senalp et al. [9] performed fatigue analysis by FEM

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simulation under dynamic walking load of four different geometries. All stem shapes were safe and the best stem shape against fatigue failure was determined. Fiorentino et al. [10] tested one commercial and 3 different stem geometries using FEM simulations under cyclic load according to ISO 7206. The result was two of the proposed stems passed the tests and showed possibility of improvement.

Shape optimization is also effective because of its ability to help designers optimize many features of the prosthesis such as shape, durability, etc. For example, Katoozian and Davy [11] introduced three-dimensional shape optimization of a femoral prosthesis in which the geometry was defined in terms of longitudinal and cross-sectional shape variables. Kayabasi et al. [9,12,13] and Tanino et al. [14] followed a similar approach but with different objective functions. Kayabasi's study used maximum von Mises stress of a femoral prosthesis as an objective function to minimize while Tanino's study used the cement's maximum von Mises stress as an objective function. In addition, Sabatini and Goswami [15] introduced another approach for shape optimization. Various cross-sections were applied to a fixed prosthesis profile. Since the profile was fixed, this prosthesis was fit with bone for which it was designed. These studies achieved their goals of finding optimal prosthesis shapes, but the designs obtained are optimal for only one objective. There is no confirmation that it is the best solution for other components in the system.

Most of the studies above concentrated only on the strength of a designed hip stem. However, a large number of failures for cemented femoral hip prostheses are the result of aseptic loosening [16] which is possibly caused by cracking of cement mantle. Ramos et al. [17] developed the design process of a cemented hip. The results show that stem geometry plays an important role in cement cracks and interface stresses. Gravius et al. [18] conducted an in vitro study of the metal-bone cement interface and the cement mantle in cemented femur stems of six different designs under cyclical loading. Significant differences between the stem designs concerning gaps in the metal-bone cement interface and cracks in the cement mantle became apparent. To avoid early mechanical damage and cement degradation, complete cement mantles with adequate thickness and fitness of components and bones is necessary [10,18–23].

The objective of this study is to discover a new design for femoral hip prostheses which is not only optimal in terms of safety of both cement and prosthesis, but also fits selected Thai femur. In order to achieve these goals, the present study uses a multi-objective shape optimization program to optimize durability of femoral hip prostheses by varying shape parameters at assigned cross-sections of the selected geometry.

2. Materials and methods

2.1. Multi-objective optimization

Multi-objective optimization helps to solve problems with limits, constraints, and contradictory objective functions of prostheses. Once the optimization is performed, it generates a series of optimal solutions. Objective functions resulting from each solution are not significantly better than those of others. Decision-making is needed in order to select the solution that is the most appropriate for the problem. The multi-objective shape optimization program used in this study consists of two major programs, NSGA-II and ANSYS. NSGA-II [24], which is written in C language, uses a genetic algorithm to perform its task as an optimization program. ANSYS is a finite element program used for stress calculation. ANSYS can run automatically using the ANSYS Parametric Design Language (APDL). An interface methodology was developed for use between the two programs [25]. The program starts when NSGA-II generates design parameters and writes them into an interface data file. Then ANSYS reads the parameters and uses them to create a three-dimensional model of a hip prosthesis, cement and femur following APDL commands. After ANSYS finishes calculating, it writes objective functions into the data file which is read and used by NSGA-II for the optimization process. A schematic diagram of the interface methodology is shown in Fig. 1.

2.2. Hip prosthesis geometry design

The designed hip prosthesis is divided into five parts as shown in Fig. 2. Various types of cross-sectional area, such as a circle, oval rectangle, and oval trapezoid, are assigned to each portion of the prosthesis. Since the shape of the head portion must be a commercially used Morse taper in order to connect with a femoral head at the superior end, the cross-sectional area of the head portion must be a circle. The cross-sectional area of the neck portion is also assigned to be a circle because it directly connects to the head portion. An oval rectangular cross-sectional area is assigned at the body portion and distal portion as it is the best shape for the femoral canal. The prosthesis is designed to have a constant taper in the sagittal plane, thus an oval trapezoid is located at the render portion. The overall geometry of the hip prosthesis used in this study is shown in Fig. 3. The cross-sectional areas of section A–A′ and those of higher sections are circular. Those of section B–B′, C–C′ and D–D′ are oval trapezoids and those of section E–E′, F–F′, and G–G′ are oval rectangles.

2.3. Finite element model

MRI image in DICOM format were collected from 47 Thai femurs which belonged to 25 female and 22 male patients. The age of the patients ranged from 49 to 80 years (average, 63.5 years). DICOM data were imported to Mimics software (version 11) for 3D reconstruction of femur models. Then, geometric dimensions such as femoral head offset and canal width at each level were measured. K-means clustering algorithm was applied to classify the geometric dimensions of the femurs and three classes including small-sized, medium-sized and large-sized Thai femurs were determined. The selected femur model used in this paper is the small-sized Thai femur, which is cut at the lesser trochanter to form an implantable femur as shown in Fig. 4.

An APDL command is written to create a three-dimensional hip prosthesis model according to the selected prosthesis geometry. A layer of 2 mm thick cement is shaped to conform to the prosthesis shape [20]. Construction of the three-dimensional finite element model starts with the creation of key points for design parameters.

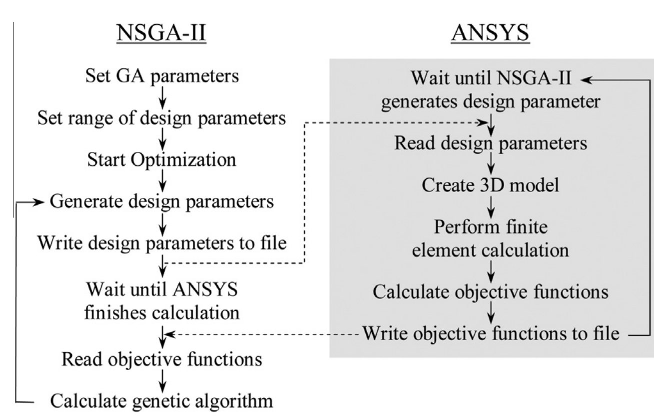

Fig. 1. Schematic of interface methodology.