Computer-Aided Design 51 (2014) 31–38

Contents lists available at ScienceDirect

Computer-Aided Design

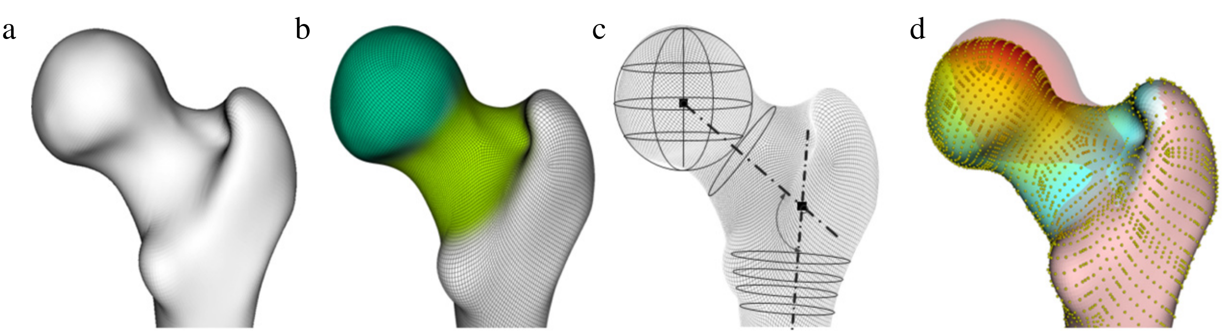
journal homepage: www.elsevier.com/locate/cad

Function-based morphing methodology for parameterizing patient-specific models of human proximal femurs☆

Byoung-Keon Park[a], Ji-hoon Bae[b], Bon-Yeol Koo[c], Jay J. Kim[c,*]

[a] University of Michigan Transportation Research Institute, Ann Arbor, MI, USA
[b] Department of Orthopedic Surgery, Korea University Hospital, South Korea
[c] School of Mechanical Engineering, Hanyang University, Seoul, South Korea

GRAPHICAL ABSTRACT



The pipeline of the proposed FBM method: (a) Import of a patient-specific femur model, (b) segment the model into functional regions using fitted primitives, (c) estimated of the functional parameters for each segmented region, and (d) morph the model by altering the functional parameters using FBM fields

HIGHLIGHTS

- Function-based morphing (FBM) method for patient-specific proximal femur was proposed.
- FBM morphs the patient-specific model based on the biomechanical functions.
- Detailed algorithms for a robust morphing are presented in this paper.
- FBM provides a systematical way to analyze biomechanical responses of a specific bone.

ARTICLE INFO

Article history:
Received 1 May 2013
Accepted 8 February 2014

Keywords:
Parameterization
Function-based morphing
Biomechanical function
Proximal femur geometry
Patient-specific model

ABSTRACT

This paper presents a novel morphing method for parameterizing patient-specific femur models based on femoral biomechanical functions. The proposed function-based morphing (FBM) method aims to provide a robust way to independently morph each partial functional region of the target femur structure by simply assigning the given functional parameters such as the femoral head diameter, neck length and diameter, and neck inclination angle. FBM includes three steps: (1) feature recognition to segment a femoral model into functional regions, (2) simplification to estimate the original parameters of the model and to define the morphing criteria as geometrical constraints, and (3) morphing to obtain the required shape by applying FBM fields that convert the terms of parametric changes into morphing vector terms for each segmented region. The proposed method was validated on a total of 48 patient-

☆ This paper has been recommended for acceptance by Charlie C.L. Wang.

* Corresponding author. Tel.: +82 2 2220 0572; fax: +82 2 2292 7758.
E-mail address: jaykim@hanyang.ac.kr (J.J. Kim).

http://dx.doi.org/10.1016/j.cad.2014.02.003

specific femur models. These models were parameterized and morphed without unexpected parametric changes, and the averaged error between the required parameters and the re-estimated parameters after morphing was 3.47%. Our observations indicate that the variation models developed in this study can be used as fundamentals for various functional sensitivity analyses for predicting changes in biomechanical responses due to the morphological changes of a subject-specific femur structure.

1. Introduction

The morphology of a bone is closely associated with its biomechanical responses [1], but this morphology can be changed due to aging or orthopedic surgery. Thus, much research efforts have been focused on evaluating the effects of morphometric variations of a bone. In these studies, the finite elemental analysis (FEA) approach has been employed to analyze the relationship between bone structures and their biomechanical responses [2–4]. Traditionally, there have been two approaches to describe bone structures in FEA: statistical and patient-specific. Statistical models include the standardized geometry and generic properties representative of their population, and it has been proven that these models are suitable for parameterizing objects, such that aspects of the model geometry and mechanical properties are defined in a way that they can be varied by specifying a parameter value [5,6]. With these statistical approaches, however, the models are limited in their sample population, meaning that a statistic model cannot represent the complex detail of a particular subject that is not included in its population [2]. Unlike statistical models, patient-specific models incorporate the more detailed information of a patient, so that they have been widely used to more accurately analyze individual responses in biomechanics research [1,7–11]. As the morphology of a proximal femur affects the biomechanical functions and responses, numerous studies have extensively experimented with how the morphology influences the responses of the specific femoral specimens. Kukla et al. [12], for example, reported that the femoral neck diameter is the most crucial factor affecting its fracture among the femoral geometry parameters. Lenaerts et al. [13] showed that femoral neck length mainly affects hip contact forces such as anterior–posterior, vertical, and medio-lateral components during gait. Hence, a reliable parametric morphing methodology for a patient-specific model has significance in its usability for various applications such as systematic morphological sensitivity analyses, pre-operative surgery plans, and other biomechanical simulations. However, the morphology of a patient-specific bone structure cannot easily be parameterized due to its geometric complexity. In other words, the complex geometry of a proximal femur structure comprises several partial regions such as femoral head, neck, and trochanteric regions. Each region, serving specific biomechanical and anatomical functions, is continuously connected to the other regions without explicit boundaries; therefore, it has proven challenging to independently parameterize the geometry of each partial region to obtain specific functional responses.

The main objective of this paper is to provide a function-based morphing (FBM) method to parameterize 3D proximal femur models, so that a series of morphed models can be obtained from a single patient-specific femur structure by simply altering functional parameters, in order to systematically analyze the biomechanical sensitivity of the target femoral structure. To achieve this purpose, three major requirements have to be satisfied:

- femoral morphology satisfying the required functional parameters has to be obtained in an intuitive way of simple parametric adjustments;

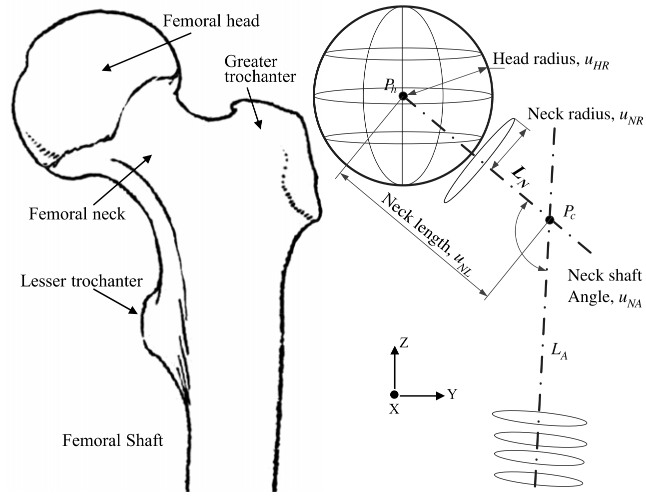


Fig. 1. The femoral structure of the proximal part and the functional parameters of each region.

- each functional region has to be morphed independently without unexpected parametric changes and geometric distortions; and
- geometric quality as an FE model should be preserved during morphing.

To meet these requirements, we present several algorithms including a functional segmentation, parameter estimation, and morphing algorithm based on the biomechanical functions in the following sections. In these algorithms, we basically design FBM fields dedicated to the proximal femur using the fitted primitives to each functional region as morphing criteria. These morphing fields are used to translate the terms of functional parameters such as femoral head diameter, neck diameter and length, and neck inclination angle into geometrical morphing terms. A total of 48 femur models were experimented on to examine the feasibility of the proposed morphing method, and the result is discussed in the last part of this paper.

2. Function-based morphing method

The proximal femur structure comprises anatomically significant regions such as the femoral head, neck, lesser and greater trochanters, and so on. These regions have been described in related studies by specific parameters, as depicted in Fig. 1. The parameters are not only closely associated with the proximal femur geometry, but also related to the biomechanical functions of the bone itself so that they have been considered as FUNCTIONAL parameters in previous studies in the biomechanical field [10,13,14]. The femoral head diameter (FHD) and femoral head center (FHC), which determine the rotational center of hip joint, are related to the stability of the joint [7]. The femoral neck diameter (FND) is