



Predictive statistical models of baseline variations in 3-D femoral cortex morphology



Ju Zhang^{a,*}, Jacqui Hislop-Jambrich^b, Thor F. Besier^{a,c}

^a Auckland Bioengineering Institute, University of Auckland, Auckland, New Zealand

^b Centre for Medical Research and Development, Toshiba Medical, Sydney, Australia

^c Department of Engineering Science, University of Auckland, Auckland, New Zealand

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ABSTRACT

Quantifying human femoral cortex morphology is important for forensic science, surgical planning, prosthesis design and musculoskeletal modeling. Previous studies have been restricted by traditional zero or one dimensional morphometric measurements at discrete locations. We have used automatic image segmentation and statistical shape modeling methods to create predictive models of baseline 3-D femoral cortex morphology on a statistically significant population. A total of 204 femurs were automatically segmented and measured to obtain 3-D shape, whole-surface cortical thickness, and morphometric measurements. Principal components of shape and cortical thickness were correlated to anthropological data (age, sex, height and body mass) to produce predictive statistical models. We show that predictions of an individual's age, height, and sex can be improved by using 3-D shape and cortical thickness when compared with traditional morphometric measurements. We also show that femoral cortex geometry can be predicted from anthropological data combined with femoral measurements with less than 2.3 mm root mean square error, and cortical thickness with less than 0.5 mm root mean square error. The predictive models presented offer new ways to infer subject-specific 3-D femur morphology from sparse subject data for biomechanical simulations, and inversely infer subject data from femur morphology for anthropological and forensic studies.

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1. Introduction

Human femoral anatomy is important to many fields of study owing to its large relative size and the functional importance it confers through locomotion. The durability of the femoral cortex means that it often stays intact over time, providing a long-lived and valuable repository of information for anthropologists. The surface shape of the femur correlates to anthropological features including age, sex, stature, gait and general health [1–4]. As such, baseline statistics and correlations concerning femoral cortex morphology are critical for accurate predictions in the fields of anthropology and forensic science.

The functional and clinical importance of the femur means that it is also an integral component of lower-limb computational musculoskeletal models. The accuracy and validity of these models to represent a specific population depend on femoral shape [5,6] and cortical thickness for its mechanical contribution [7]. Therefore, the

ability to rapidly generate femur models that accurately represent shape and cortical thickness will help to streamline simulations and improve their accuracy and validity for surgical planning and prosthesis testing and design.

Caliper measurements of the femur based on surface anatomical landmarks have been the foundation of femur morphological studies [8]. Recent studies have established baseline measurements on femurs or partial femurs from samples of varying sizes [9,10]. Caliper-like measurements are also still used to provide local measures of cortical thickness [7,11]. While simple to collect, these measurements only provide an abstraction of full 3-D morphology at local sites. Medical imaging enables the collection of volumetric images from which the femoral cortex can be segmented. The development of statistical shape analysis [12] has allowed variations in the 3-D shape of the femur to be studied in detail [13–15], capturing more information than caliper-based measurements. A major limitation has been the sample size used. Heinze et al. [15] used 235 specimens, but only of the distal femur. Waarsing et al. [16] studied a cohort of 222 subjects, but was limited to the proximal femur. Mahfouz et al. [13] used 166 whole femurs while other studies use sample sizes less than 100.

* Corresponding author Tel.: +64 9 373 7599x86916; fax: +6493677157
E-mail address: ju.zhang@auckland.ac.nz (J. Zhang).

The other major limitation of previous femur statistical shape studies was the exclusion of whole-bone cortical bone thickness from the analysis. Studies have assessed cortical thickness at a few discrete locations [11,17]. Recent work by Serrurier et al. [18] provided the first statistical model of femur cortical thickness. It was, however, limited by a small elderly dataset. Work by Treece et al. [19] provided a method to accurately measure cortical bone thickness over the whole surface of a bone from clinical CT images. Using this method, we established a method for automatically segmenting femur geometry and measuring cortical thickness from CT images [20].

The novelty of this work is in establishing predictive models between 3-D cortical morphology and anthropological data of age, sex, height, and body mass, augmented by morphometric measurements. We quantify the accuracy of our predictive models and propose a model using very sparse patient information and morphometrics for patient-specific femur model generation. In the next section, we detail the training of statistical models on 204 human femurs for two use cases. First, regression models for predicting anthropological information from cortical morphology for anthropological and forensic applications. Second, regression models for predicting 3-D cortical morphology from anthropological information for downstream computational modeling, e.g. kinematic analysis and hip and knee implant finite element modeling. We present the accuracy of our predictive models in Section 3, and discuss their implications and limitations in Section 4.

2. Methods

This study was carried out on 204 X-ray computed tomography (CT) images collected from routine post-mortem imaging at the Victorian Institute of Forensic Medicine (VIFM), Melbourne, Australia, with ethical approval from the VIFM and the University of Melbourne. All subjects died of unexpected causes and were scanned on arrival at the VIFM mortuary which means that the vast majority of CT scans were performed only hours after death. Each cadaver was imaged using a Toshiba Aquilion 16 MDCT scanner (Toshiba Medical Systems Corporation, Tokyo, Japan), with 0.9 mm in-slice pixel spacing and 1.6 mm slice spacing. Quantitative CT assessments were performed using the Mindways QCT analysis toolset (Mindways Software, Inc. Austin, TX, USA) for bone mineral density (BMD) and associated 3D measurements. The images were selected from a pool of 327 images collected by a medical imaging specialist for a morphometric study [10]. Sixty-five images were excluded due to bone pathologies (such as bone cancer and osteoarthritis), deformities, trauma, and imaging artefacts. A further 58 images were excluded due to poor segmentation results (see next section). The remaining 204 images capture a typical western urban population, with age at death ranging from 19 to 95 years old and include 110 males and 94 females. For males, there were approximately 17 subjects per 10-year age group between the ages of 20 to 70, and approximately half that in other age groups. For females, there were approximately 14 subjects per 10-year age group between the ages of 30 to 80, and about half that in the other age groups. Distributions of age, height, and body mass are provided as supplementary material.

2.1. Segmentation and measurements

The right femoral cortical surface in each CT image was automatically segmented and converted into digital 3-D models, on which shape analysis and morphometric measurements were then performed. The segmentation and modeling process used Active Shape Modeling [21] for automatic segmentation, and cortical thickness mapping [19] for automatic cortical thickness measurements over the entire femoral surface. These two methods were

used to progressively customize an anatomical region-based atlas femur mesh to the cortical surfaces in a CT image. Details of the segmentation and modeling pipeline are described in our previous work [20]. Briefly, after locating the right femur by its femoral shaft, an active shape model trained on 31 randomly selected and manually segmented femurs [22] was used to segment the femur by deforming an atlas mesh to the femoral surface. The CT image was then analyzed normal to the mesh to calculate the cortical thickness and the positions of the inner and outer cortical surface using the cortical thickness mapping method. The analysis was performed over the whole femoral surface to obtain a more accurate femoral surface mesh and a smooth cortical thickness field interpolated on the mesh.

In a validation experiment, automatic segmentations were compared with manual segmentations. Surface segmentation error was calculated as the root-mean-squared (RMS) distance between each vertex on the manually segmented mesh and its closest point on the automatically segmented mesh. Cortical thickness error was calculated as the RMS difference in thickness values at corresponding points as defined above. Over 17 femurs, automatically segmented meshes had an average RMS error of 0.74 mm over the entire surface, and cortical thickness had an average RMS error of 0.61 mm [20]. These results were obtained on images not part of the training set with the same resolution as those used in this study. However, improved image resolution may lead to better accuracy. After excluding images with pathologies, deformities and image artefacts, 262 images were segmented using the automatic method. Each segmented femur was visually inspected and 58 femurs were excluded due to obviously poor segmentation accuracy or mesh artefacts such as intersections and inversions. A total of 204 femur meshes were left for statistical analysis.

Femur morphometric measurements (Fig. 1) were automatically taken on the surface meshes segmented from CT images. As a single atlas mesh was customized to each femur during segmentation, each femur surface was parameterized by a common coordinate system, allowing anatomical features to be defined by their parametric coordinates within a mesh patch (e.g. femoral epicondyles), or by its group of mesh patches (e.g. femoral neck). For each femur mesh, anatomical landmarks and axes were calculated to provide a coordinate system for measurements. Morphometric measurements were then automatically taken from each mesh. The accuracy of the automatic measurements was compared with manual measurements performed by an imaging scientist. Relative error between automatic and manual measurements was between 0.15% (femoral length) and 6.52% (mid-femoral width). Despite these errors, we will show in our results that the automatic measurements are capable of making accurate predictions of 3-D femur morphology. Morphometric measurements as well as anthropological data are summarized in Table 1. The measurement definitions and details of their validation are included in this article's supplementary material.

2.2. Statistical models of 3D shape and cortical thickness

Principal component analysis (PCA) [23] was performed on the population of femur models and cortical thickness maps to model the main modes of variations. PCA was performed on:

- Mesh node coordinates to produce a model of femur shape variation.
- Mesh node cortical thickness values to produce a model of cortical thickness variation.
- Both node coordinates and cortical thickness to produce a model of shape variations correlated with cortical thickness variations.

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