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Increasing shape modelling accuracy by adjusting for subject positioning: An application to the analysis of radiographic proximal femur symmetry using data from the Osteoarthritis Initiative ☆

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ABSTRACT

In total hip arthroplasty, the shape of the contra-lateral femur frequently serves as a template for preoperative planning. Previous research on contra-lateral femoral symmetry has been based on conventional hip geometric measurements (which reduce shape to a series of linear measurements) and did not take the effect of subject positioning on radiographic femur shape into account. The aim of this study was to analyse proximal femur symmetry based on statistical shape models (SSMs) which quantify *global* femoral shape while also adjusting for differences in subject positioning during image acquisition. We applied our recently developed fully automatic shape model matching (*FASMM*) system to automatically segment the proximal femur from AP pelvic radiographs to generate SSMs of the proximal femurs of 1258 Caucasian females (mean age: 61.3 SD = 9.0). We used a combined SSM (capturing the left and right femurs) to identify and adjust for shape variation attributable to subject positioning as well as a single SSM (including all femurs as left femurs) to analyse proximal femur symmetry. We also calculated conventional hip geometric measurements (head diameter, neck width, shaft width and neck-shaft angle) using the output of the *FASMM* system. The combined SSM revealed two modes that were clearly attributable to subject positioning. The average difference (mean point-to-curve distance) between left and right femur shape was 1.0 mm before and 0.8 mm after adjusting for these two modes. The automatic calculation of conventional hip geometric measurements after adjustment gave an average absolute percent asymmetry of within 3.1% and an average absolute difference of within 1.1 mm or 2.9° for all measurements. We conclude that *(i)* for Caucasian females the *global* shape of the right and left proximal femurs is symmetric without isolated locations of asymmetry; *(ii)* a combined left–right SSM can be used to adjust for radiographic shape variation due to subject positioning; and *(iii)* adjusting for subject positioning increases the accuracy of predicting the shape of the contra-lateral hip.

Introduction

Anteroposterior (AP) pelvic radiographs are widely used in clinical practice for the assessment of skeletal disorders such as hip osteoarthritis or osteoporosis. In total hip arthroplasty, preoperative templating based on AP pelvic radiographs is an important step in predicting features such as implant size, position and orientation [1–3]. Depending on the severity of disease, for example in cases of arthritic hips or osteoporotic fractures, the AP view of the affected side may not provide sufficient information to serve as a template. In such cases, the shape of the contra-lateral femur frequently serves as a template for orthopaedic surgery planning.

Several studies have been undertaken to analyse bilateral femoral symmetry in humans that have suggested that such symmetry can be assumed [4–8]. However, past studies have either focussed on non-geometric aspects of femoral symmetry (e.g. structural properties), or have used pre-defined conventional hip geometric measurements (e.g. femoral head diameter or neck-shaft angle) and sample sizes have been small. Conventional hip geometric measurements reduce shape to a series of linear measurements rather than taking global shape into account. More recently, statistical shape models (SSMs) have been introduced for detailed morphometric analysis of *global* bone shape [9–13]. SSMs describe every shape by the sum of a mean shape and a linear combination of a number of shape modes which allows the quantification of overall proximal femur shape for each subject.

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In analyses of hip morphometry, SSMs have been successfully used to identify key features of bone shape that contribute to the progression of radiological hip osteoarthritis, to predict osteoporotic hip fractures, and to analyse genetic contributors to hip osteoarthritis [10,11,14–16].

We have recently developed a fully automatic shape model matching (*FASMM*) system to rapidly and accurately segment the proximal femur from AP pelvic radiographs and to represent the shape of the proximal femur using an SSM [17]. The generated SSM allows the quantitative description of global proximal femur morphology. However, as AP pelvic radiographs only give a two-dimensional projection of what is a three-dimensional structure, the projected radiographic shape will differ depending on the positioning of the subject (e.g. pelvic or internal/external leg rotation during image acquisition). Hence, relying on measurements taken directly from the AP projected view without any adjustment for subject positioning may lead to an incorrect representation of the actual shape.

The specific aims of this study were therefore to: (1) analyse the symmetry of the left and right proximal femurs via using SSMs to quantify *global* proximal femur morphology; (2) develop an SSM-based method that adjusts for subject positioning during image acquisition; and (3) assess the impact of subject positioning on the projected radiographic shape via the analysis of hip geometric measurements automatically calculated from the output of the *FASMM* system.

Materials and methods

Dataset

Data used in the preparation of this article were obtained from the Osteoarthritis Initiative (OAI) database, which is available for public access at http://www.oai.ucsf.edu/. We used radiographs from release 0.E.1 of the 'Images' dataset. Clinical data came from version 0.2.2 of each of the clinical datasets 'Enrollees', 'Subject Characteristics', 'Medical History', and 'Physical Exam'. Demographic data for each subject included body mass index (BMI) and age at enrolment.

Baseline AP pelvic radiographs from 4796 subjects (2804 females and 1992 males) were available. For our analyses, we selected the larger subgroup of 2124 Caucasian females to limit the variation that might occur due to the differences in hip joint shape between males and females [18,19,6,20] or between ethnic groups [21,22] and thereby increase the likelihood of identifying shape variation that was attributable to subject positioning. From this dataset of 2124 Caucasian females, we also excluded subjects who had had hip replacement surgery at baseline or with a self-reported diagnosis of hip osteoarthritis at baseline or at 48 months follow up as recorded in the OAI database. The reason for exclusion based on these latter criteria was that the *FASMM* system had been trained previously on OA-unaffected proximal femurs [17,20]. Radiographic scoring of all radiographs is not currently available for the OAI radiographs and so exclusion on the basis of radiographic osteoarthritis was not undertaken. Hence, it is possible that subjects with radiographic evidence of osteoarthritis in the absence of a diagnosis of osteoarthritis may have been included in our dataset. There was no evidence, however, that this had a negative impact on the performance of the *FASMM* system (see Section 3.1). Application of these exclusion criteria reduced the dataset to 1610 baseline AP pelvic radiographs of which 1282 included both the left and right proximal femurs without any occlusions and were selected for further study. Table 1 summarises key features of relevant medical history for the 1282 subjects included in this study.

Table 1
Summary statistics for the 1282 subjects included in this study (mean age: 61.3 SD = 9.0; mean BMI: 27.3 SD = 5.0).

	# Subjects out of 1282	
	At baseline	At 48 months
Any hip pain, aching or stiffness in past 12 months	741	660
Infrequent knee pain	492	566
Frequent knee pain	534	486
Self-reported knee osteoarthritis	234	288
Self-reported rheumatoid arthritis	50	54

The FASMM system

We used the previously described *FASMM* system to accurately and fully automatically segment the proximal femur in pelvic radiographs [17]. As previously described [20], the system was trained on 1105 AP pelvic radiographs from subjects recruited in Stage 2 of The arcOGEN Consortium study [23]. The *FASMM* system segments the proximal femur by first detecting it in the radiograph and then outlining its contour using 65 points (see Fig. 1a) that are placed in consistent positions across all images. The system uses a front-view femur model that excludes both the lesser and greater trochanters.

As previously described [20], the contour points returned by the *FASMM* system are used to represent the shape of the proximal femur as an SSM. This provides a *global* representation of shape rather than reducing shape to a series of linear measurements which enables the analysis of shape variation across datasets. Based on a number of points in a set of images, an SSM is trained by applying principal component analysis to the aligned shapes [24]. This yields a linear model of shape variation which represented the position of each point l using

$$\boldsymbol{x}_l = T_\theta\,(\bar{\boldsymbol{x}}_l + \boldsymbol{P_l b} + \boldsymbol{r}_l) \tag{1}$$

where $\bar{\boldsymbol{x}}_l$ was the mean position of the point in a suitable reference frame, $\boldsymbol{P_l}$ was a set of modes of variation, $\boldsymbol{b}$ were the shape model parameters, $\boldsymbol{r}_l$ allowed small deviations from the model, and T_θ applied a global transformation (e.g. similarity) with parameters θ. All modes of variation in $\boldsymbol{P_l}$ are orthogonal and every mode defines a pattern of shape variation. The first mode in $\boldsymbol{P_l}$ accounts for the largest amount of shape variation across the dataset, the second mode for the largest amount of shape variation still remaining and so on. For the purpose of analysis of shape variation, the inclusion of the modes that describe 95% of the overall shape variation is accepted in the field as an appropriate cut-off to minimise noise [25–27].

Adjusting for subject positioning

We applied the *FASMM* system to fully automatically segment the left and right proximal femurs from the radiographs of all subjects. We used the output of the *FASMM* system (i.e. 65 contour points per proximal femur per subject) to generate a combined SSM that included both the left and right proximal femurs at the same time and hence was derived from 130 contour points as shown in Fig. 1b. Since AP pelvic radiographs only give a two-dimensional projection of the three-dimensional proximal femur, building a combined model allowed us to analyse whether the projections of the left and right proximal femurs varied in a symmetrical manner. The aim was to identify whether there were any oppositional patterns of asymmetric shape variation i.e. patterns where the shape variation between the left and right sides were similar but in opposite directions. Modes of variation that were clearly attributable to an oppositional asymmetric pattern of shape variation between the left and the right sides (e.g. due to subject positioning during image acquisition) were excluded. This was achieved by setting the relevant shape model modes in $\boldsymbol{b}$ to zero (see Eq. (1)) and subsequent re-evaluation of all 130 points $\boldsymbol{x}_l$ for every subject. To analyse the difference in shape between the point positions identified by the *FASMM* system and the point positions after exclusion of specific modes, we aligned the two point sets for every subject using a similarity transformation and calculated the mean point-to-curve distance over all 130 points. We used custom code developed in C++ for this analysis and to generate the graphics.