Medical Engineering & Physics 35 (2013) 1703–1712

Contents lists available at ScienceDirect

Medical Engineering & Physics

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

Three-dimensional reconstruction of the lower limb from biplanar calibrated radiographs

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ARTICLE INFO

Article history:
Received 20 July 2012
Received in revised form 14 May 2013
Accepted 6 July 2013

Keywords:
Three-dimensional reconstruction
Lower limbs
Surgical planning
Biplanar calibrated radiographs
Statistical model
Clinical measurements
Automation

ABSTRACT

Three-dimensional (3D) reconstruction of lower limbs is essential for surgical planning and clinical outcome evaluation. 3D reconstruction from biplanar calibrated radiographs may be an alternative to irradiation issues of CT-scan. A previous study proposed a two-step reconstruction method based on parametric models and statistical inferences leading to a fast *Initial Solution* (IS) followed by manual adjustments. This study aims to improve the IS using a new 3D database, a novel parametric model of the tibia and a different regression approach. The IS was evaluated in terms of shape accuracy on 9 lower limbs and reproducibility of clinical measurements on 22 lower limbs. Reconstruction time was also evaluated. Comparison to the previous method showed an improvement of the IS in terms of shape accuracy (1.3 vs. 1.6 and 2 mm respectively for both femur and tibia) and reproducibility of clinical measurements (i.e. 3.1° vs. 8.3° for neck-shaft-angle; 4.2° and 5° vs. 5° and 6° for tibial and femoral torsion respectively). The proposed approach constitutes a considerable step towards an automatic 3D reconstruction of lower limb.

1. Introduction

Three-dimensional (3D) reconstruction of bones is becoming crucial in clinical routine for surgical planning and clinical outcome evaluation. Automatic 3D reconstructions and extraction of relevant clinical parameters from these reconstructions is therefore more and more substantial. Two types of approaches are mainly used depending on the size of the original set of images: extensive set of images (ESI) and reduced set of images (RSI).

ESI-based approaches (i.e. computerized tomography or CT-scan) may be expensive, time-consuming and additionally require heavy examination and irradiation for the patient [1]. Additionally, the exam is performed with the patient in a reclining position, though measurements of space alterations would be questionable due to a high sensitivity with respect to the measurement protocol [2] (e.g. femoral and tibial torsion), since calculation of these clinical measurements (CM) is more relevant in a standing (weight bearing) position [3,4]. ESI-based approaches are based on cross-sectional images segmentation, to generate a 3D mesh (i.e. "marching cubes" algorithm [5]). However this complex method generates 3D models which are hardly interpretable in terms of anatomical regions. Thus automatic calculation of accurate and relevant CM is challenging.

On the other hand, RSI-based approaches generally imply lighter exams and processing, as well as a standing position of the patient. Since the recorded data amount is lower than in ESI-based approaches, models are invoked to extrapolate the non-visible structures. For instance, statistical shape modelling (SSM) aims at estimating the envelope shape of an object as a finite set of points. A principal component analysis (PCA) [6] is performed to a learning database of 3D shapes in order to model shape variations. New 3D shapes are then derived by means of the PCA model, using a small set of visible landmarks, which are manually extracted from the RSI. This input is used for guiding the deformation of a statistical model of shape, thus obtaining the 3D reconstruction. To refine the 3D reconstruction for subjects with different morphologies (in regards with the learning database), SSM can be complemented by an elastic 2D/3D non-rigid matching. Such methods were proposed for the vertebrae [7,8], spine [9,10], proximal femurs [11,12] and pelvis [13]. Nevertheless, SSM methods strongly rely on the learning database; in order to reconstruct accurately new patients, the learning database should cover the main inter-individual variations both for normal and pathologic subjects. To our knowledge, such methods have not been proposed for the whole lower limb.

An alternative RSI-based approach was also proposed [14] based on parametric modelling and taking anatomic and clinical considerations into account. Instead of using the full set of points as proposed by SSM modelling, statistics are performed on anatomical *Descriptive Parameters* (DP) extracted from the surface of interest. This approach appeared particularly efficient in providing a fast,

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http://dx.doi.org/10.1016/j.medengphy.2013.07.002

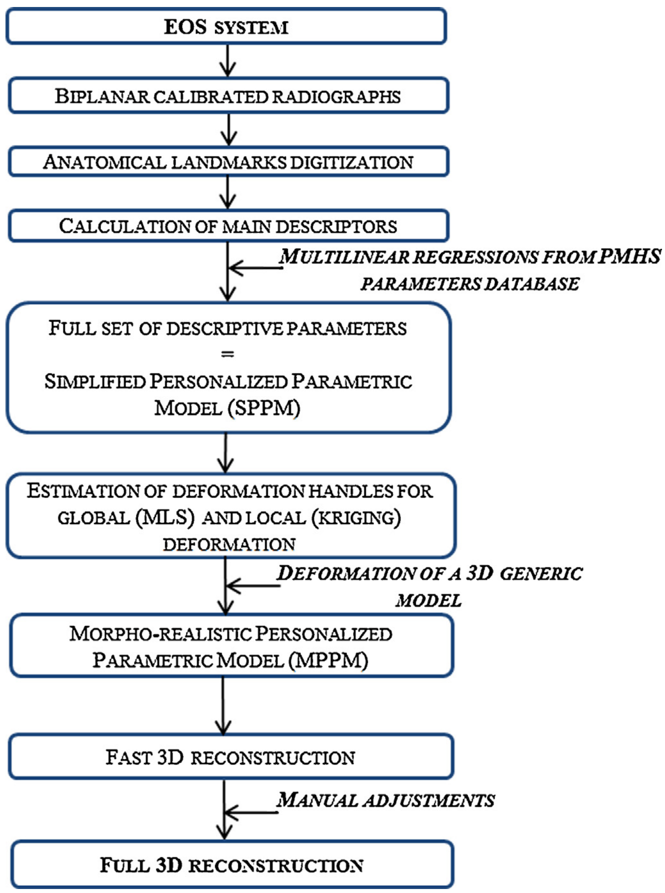

Fig. 1. Schematization of the 3D reconstruction method of the lower limbs from biplanar calibrated radiographs obtained via the EOS system.

robust and anatomically interpretable initial 3D reconstruction or *Initial Solution* (IS) for a much larger pool of subjects. Statistical inferences from DP are used to calculate deformation handles for global deformation and control points for local adaptation; the IS is obtained after deformation of a morpho-realistic personalized generic shape by means of the estimated deformation handles and control points. Furthermore, the model is then 'retro-projected' on the RSI for possible adjustments. These models have been used to reconstruct the spine, pelvis and upper limbs from radiographs [15–18].

In this context, 3D reconstruction of lower limbs from biplanar calibrated radiographs has been proposed [19] (Fig. 1). Geometric primitives such as spheres, cylinders and ellipses were used to describe the lower limbs. These primitives were defined through the DP in terms of: radius, geometrical centre coordinates among others. A statistical model based on multi-linear regressions, obtained from a training database, links a reduced set of DP (i.e. *main descriptors*) to the full set of DP. In clinical routine, *main descriptors* are manually digitized on the biplanar-calibrated radiographs, and the full set of DP is then derived by means of the statistical model. Subsequently, geometric primitives are estimated from the full set of DP, providing a 3D geometric representation, referred to as the simplified personalized parametric model (SPPM). Deforming the morpho-realistic 3D generic mesh into the SPPM leads to the morpho-realistic personalized parameterized model (MPPM), thus yielding the IS.

Two reconstruction levels were proposed [19]: (1) 'fast 3D', where IS was obtained without manual corrections, and (2) 'full 3D', for a more accurate 3D reconstruction, by performing manual adjustments to the IS. The second reconstruction level, is divided in two steps: 'full 3D-I', where the 3D shape can be manually adjusted by means of moving least squares (MLS) [20] handles, and the 'full 3D-II', where further local adjustments can be manually performed following a correspondence algorithm [21] and kriging interpolation [22]. This two-steps method [19] offers a fast and accurate 3D reconstruction for lower limbs and is already implemented into clinical routine. However, some limitations remain: (1) the learning database of femurs and tibias used to build the statistical model has been obtained by reconstructions from biplanar radiographs using former reconstructions methods [23], providing less accurate reconstructions than ones from CT-scans; (2) the parametric model is only focused on the femur; (3) the use of classic regression techniques such as multi-linear regressions instead of more adapted approaches (e.g. partial least squares or PLS) [24]; (4) manual corrections are time consuming. In addition, more image processing automation is required for a larger use in clinical routine and the performance would rely on the accuracy of the initial shape provided by the 'fast 3D' reconstruction.

For a better integration to clinical routine workflow, this study focused on improving the 'fast 3D' reconstruction of lower limbs, by reducing manual corrections. A CT-scan morphometric database of femurs and tibias, a new parametric representation for the tibia and a new statistical model are proposed to enhance the accuracy of the 3D reconstruction.

2. Materials and methods

The reconstruction process of the lower limbs begins when an operator digitizes anatomical landmarks on biplanar calibrated radiographs; those landmarks were used as input of a statistical model, whose output was employed for obtaining the 3D reconstruction. The proposed approach: (1) the building of a statistical model; and (2) the 3D reconstruction, following the output provided by the statistical model.

2.1. Subjects and database

The database included: (1) *Cadaveric subjects*: 14 post mortem human subjects (PMHS) obtained from the Cochin hospital (Paris, France), after gaining approval of both the CEESAR (Centre Européen d'Etudes de Sécurité et d'Analyse des Risques) and Paris Descartes University's ethics committee. The sample was composed of 12 males and 2 females (mean age 74.6 years, range [60–87]); Axial CT-scan slices were collected from head to feet [0.75-mm-thickness, 0.5 mm inter-slice distance] with subjects in a supine position, arms along the body sides. A qualitative check was performed to ensure that the images were correctly sorted. Images were manually segmented, and the whole lower limbs were reconstructed from ankle to pelvis using the software Avizo®. From this database, 26 femurs (13 right – 13 left) and 24 tibias (12 right – 12 left) were selected for the study, excluding those with healed fractures or implants.

(2) *Anatomical samples*: which comprised 30 non-pathologic proximal femurs recorded at Lariboisière hospital (Paris). Samples were taken from human cadavers within 10 days of death and frozen at −20 °C, keeping the bone surface in good condition. The sample was composed of 13 males and 17 females (mean age 85, range [60–101]); Axial CT-scan slices were collected from the femoral head to the upper diaphysis [1-mm-thickness, 1 mm inter-slice distance]. Proximal femurs contours were manually segmented and the 3D reconstructions were thus extracted.

In summary, the CT-based database comprised 56 femurs (26 complete – 30 proximal) and 24 tibias. 3D surfaces were modelled by a triangular mesh.