Determination of Pelvic Orientation from Ultrasound Images Using Patch-SSMs and a Hierarchical Speed of Sound Compensation Strategy

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Abstract. In the field of computer assisted orthopedic surgery (CAOS) the anterior pelvic plane (APP) is a common concept to determine the pelvic orientation by digitizing distinct pelvic landmarks. As percutaneous palpation is - especially for obese patients - known to be error-prone, B-mode ultrasound (US) imaging could provide an alternative means. Several concepts of using ultrasound imaging to determine the APP landmarks have been introduced. In this paper we present a novel technique, which uses local patch statistical shape models (SSMs) and a hierarchical speed of sound compensation strategy for an accurate determination of the APP. These patches are independently matched and instantiated with respect to associated point clouds derived from the acquired ultrasound images. Potential inaccuracies due to the assumption of a constant speed of sound are compensated by an extended reconstruction scheme. We validated our method with in-vitro studies using a plastic bone covered with a soft-tissue simulation phantom and with a preliminary cadaver trial.

1 Introduction

Accurate acetabular cup placement in total hip arthroplasty (THA) procedures is very important for the clinical outcome [1, 2]. Misaligned cup prostheses could lead to a reduced range of motion, impingement or dislocation [3–5]. Computer assistance therefore potentially provides a means to support this critical step [6]. In navigated THAs, the APP is typically used as a reference plane to measure the correct cup orientation [7]. This plane is constructed using two landmarks from the bilateral anterior superior iliac spines (ASISs) and a landmark from the pubis symphysis region. These landmarks are usually digitized intra-operatively using a tracked pointer. In order to reduce the invasiveness, these landmarks are acquired percutaneously. This may result - especially for obese patients - in a certain inaccuracy, subsequently increasing the probability of cup misalignment.

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In contrast, ultrasound imaging provides a non-invasive way to visualize subcutaneous bony structures. The use of calibrated B-mode ultrasound has been proposed by several groups for detecting landmarks \cite{8, 11, 12} or for reconstructing patient-specific 3D models of the pelvis using SSMs \cite{13, 15}. The main challenge of achieving an accurate 3D reconstruction is imposed by a proper alignment of the sparse US-derived point data with the mean pelvis model. Only a close alignment to the target points can guarantee the success of the instantiation. While in \cite{13, 15} the pelvis model was manually aligned, Foroughi et al. \cite{14} used rigid registration. Another source of error occurs due to the deviation of speed of sound in the human body from the one assumed in the calibration procedure. According to Barratt et al. \cite{16}, the correct depth estimation could be biased by up to 5\% due to variations in speed of sound. However, none of the existing approaches accounts for this depth localization problem.

In this paper, we propose a new method for reconstruction of the pelvic orientation based on point clouds segmented from tracked ultrasound images. Instead of directly matching a SSM of the complete pelvis, we constructed local patch-SSMs, which are independently matched to corresponding US-derived points. Moreover, we developed a hierarchical optimization scheme, which compensates for the speed of sound difference. We evaluated our approach with in-vitro studies using a soft-tissue simulation phantom attached to a plastic bone and with a preliminary cadaver trial.

2 Materials and Methods

2.1 Patch-SSM Construction

Computed tomography datasets of 20 different patients (average age: 61.9 years, mixed gender) were semi-automatically segmented using the software tool Amira (Visage Imaging, Richmond, Australia). The extracted pelvis surface models were then rigidly aligned in a common coordinate system based on their oriented bounding box. In order to establish dense correspondences between these training models, a non-rigid registration scheme was applied. One instance, whose size was closest to the average training model size, was selected as the reference. The other (floating) surface instances were then rigidly registered in an affine sense to the reference instance. For the subsequent non-rigid registration step, all surface instances were converted to bit-volumes. The floating instance volumes were then deformed with respect to the reference volume using diffeomorphic demons algorithm \cite{17}. This method computes the displacement field between a reference and a floating image to optimally align both images. Therefore, the displacement fields between the reference volume and each floating instance volume are computed, describing the non-rigid relation between the datasets. The overall correspondences between the available training instances could then be determined by deforming the reference instance based on the computed displacement fields.