Non-iterative partial view 3D ultrasound to CT registration in ultrasound-guided computer-assisted orthopedic surgery

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Abstract
Purpose In image-guided orthopedic surgery, rigid registration of intra-operative ultrasound (US) to a pre-operative plan, developed using computed tomography (CT) scans, is an important step for providing real time surgical guidance. The ability to perform this registration accurately, automatically, and in real time is critical for enabling more effective image guidance and anatomic restoration in a number of orthopedic procedures. Several surface-based and intensity-based registration methods have been proposed before to align the US and CT data. Although relatively successful results were reported, both methods require accurate segmentation or localization of the bone surface in US data, which is a challenging task. Furthermore, typically, only partial views of the three-dimensional (3D) bone anatomy are visible in US data, and registration would only converge if a good estimation of the initial alignment between the US and CT datasets is known.
Methods We propose a 3D rigid CT to US registration method based on the alignment of local phase bone image projections. The registration is achieved by transforming the local phase bone features, calculated using 3D Log-Gabor filters, to a projection space obtained using 3D Radon transform. Validation experiments show the capability of the method in registering partial view US volumes to full view CT volume.
Results Feasibility experiments, carried out on a phantom and ten volunteer subjects, show an average surface registration, in the region where the US scans were acquired, of 0.42 and 0.78 mm, respectively.
Conclusions The proposed US to CT registration method is fully automatic, non-iterative and requires no initial alignment between the two registering datasets.

Keywords 3D ultrasound · CT · Registration · Local phase · Radon transform · Non-iterative · Phase correlation · Computer-assisted orthopedic surgery

Introduction
Recent developments in ultrasound (US) technology, primarily due to advances in computer technology and computational techniques together with advanced probe design, have enabled three-dimensional (3D) US to be efficiently and successfully used in a range of minimally invasive orthopedic surgeries as an intra-operative imaging modality [1–6]. Nevertheless, extraction of relevant anatomic information from US images continues to be challenging because US images typically contain significant speckle and other artifacts that complicate image interpretation and automatic processing. Furthermore, the 3D local geometry of the imaged bone surface and the direction of the US beam with respect to the imaged surface significantly influence the appearance of bone boundaries in US data [7]. Due to these difficulties, US was initially investigated primarily as a method to register intra-operatively collected patient data to pre-operative plan developed using computed tomography (CT) scans. To provide effective image guidance and successful anatomic
restoration in orthopedic trauma, this registration should be performed in a fully automated way in real time and under the required accuracy limits.

Due to the rigid nature of bone, most research for US to CT registration has been focused on surface-based registration approaches [8–13]. Barrat et al. [8] minimized the distances between the two surface representations obtained from US and CT images using a least square optimization scheme. The method was validated on six femur and three pelvic intact human cadavers where an average target registration error (TRE) of 1.6 mm was reported. The drawback of this method was the manual segmentation of the bone surfaces. Furthermore, an initial alignment of US and CT data was required, which was achieved using a few manually selected landmarks. Penney et al. [9] improved the robustness of the standard iterative closest points (ICP) algorithm [10] by providing a method that randomly perturbed the point cloud positions. This provided a solution to avoid the local minima and allowed the algorithm to move to a minimum with a lower residual error. Validation was performed on scans obtained from a phantom femur and showed a mean TRE of 1.17 mm. However, the need for manual extraction of bone surfaces from US data remained to be the main drawback of the proposed method. Amin et al. [11] combined three sources of information: the bone surface reflection indicated by image intensity, edge information obtained from the bone shadow region by using a directional edge detector, and a spatial prior obtained by processing a CT volume. Instead of segmenting the bone surface explicitly from the US image, these three sources of information were combined to obtain a set of regions, which are likely to contain bone surfaces. During a modified ICP registration process, these regions were refined to select data that is most consistent with the 3D shape of the bone surface from the CT data. The reported registration error results were 1.94 mm for average translation and 0.90 degrees for average rotation. The anatomic landmark-based initial registration was used as the starting point for their proposed registration process where the surgeon selected several anatomic landmarks. The overall accuracy of their system is directly related to the accuracy of the initial registration estimate, which also depends on the experience of the surgeon and the imaged anatomic region.

To alleviate the issues associated with the conventional ICP algorithm in terms of convergence, sensitivity to outliers and registration speed, Moghari and Abolmaesumi [12] proposed a point-based registration algorithm based on unscented Kalman filter (UKF) to estimate the rigid transformation parameters between the bone surfaces obtained from US and CT data. Talib et al. [13] also proposed a similar approach to UKF where they used information filters (IF) to register bone surfaces extracted from phantom femur and L4 vertebra bones. Although both of these methods achieved improvements in terms of registration speed, robustness to artifacts and accuracy, the main drawback was the need to segment bone boundaries, which was done either semi-automatically [12] or using a simple thresholding approach [13].

Rasoulian et al. [14] used a groupwise registration approach of lumbar vertebrae using the UKF approach where the bone surfaces from two-dimensional (2D) US images were automatically segmented using a dynamic programming approach [15]. The authors reported a TRE of 2.47 mm. Recently, Brounstein et al. [16] proposed a surface-based registration method based on Gaussian mixture models (GMMs). Validation was performed on a phantom and clinical pelvic scans and showed a 0.49 and 0.63 mm root mean square distance between the registered surfaces, respectively. Before the registration, a region of interest (ROI) was manually defined as the starting point for the registration algorithm to avoid the local minima problem and increase the registration speed.

The main drawback of the surface-based registration methods proposed to date is the need for accurate segmentation of bone surface in US data, which is generally an error prone task and thus limits clinical usability. Furthermore, given the small field of view of US images, these methods require accurate initialization of the registration [8,12,16].

The second category of US to CT registration methods use the image intensity information directly in order to avoid extraction of bone surfaces from US images. Brendel et al. [17,18] segmented bone surfaces from CT data using US transducer orientation information leaving only the bone surfaces that could be imaged with the US. Correct registration was defined as the one that maximized the sum of overlapping image intensity values between the segmented CT surface and B-mode US data. Although successful registration results were achieved, the method assumes that the US transducer orientation during actual scanning is known for preprocessing the CT data. In orthopedic trauma applications, such as fracture reduction, where the US transducer needs to be re-aligned after each reduction, such assumption may not be easily realized in a clinical setting. Penney et al. [19] used normalized cross-correlation as a similarity metric for registering CT and US images. Prior to registration, both datasets were converted to bone probability images using gradient, bone intensity and US shadowing artifact information. Validation experiments performed on cadaver studies showed a TRE of 1.6 mm; however, to create bone probability images from US data manual segmentation was necessary. Wein et al. [20] used the physics of US image formation and combined this with the density information from CT data to simulate US images from CT scans. This simulation process was optimized during the registration. US simulation from CT data was later extended by Gill et al. [21] for anesthesia applications. The method was validated for registering spine bone data obtained from sheep cadaver and patient-based phantoms. The reported registration accuracy was 1.25 mm for