3D bone surface extraction from ultrasound volumes: optimization of 3D phase symmetry metric and clinical evaluation for pelvic ring fractures

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Introduction: Real-time three dimensional (3D) ultrasound (US) imaging has the potential to become a dominant imaging modality in orthopaedic surgery. One barrier to its widespread use is that the appearance of bone surfaces in US remains strongly influenced by beam direction and regions corresponding to bone boundaries appear blurry with a thickness of several mm, which complicates image interpretation and automatic processing [1]. Recently, two dimensional (2D) and three dimensional (3D) local phase-based image processing methods have been shown to perform very well at locating bone surfaces in ultrasound images, with reported accuracies of better than 0.4 mm [2]. The local phase features are extracted by filtering the B-mode US image in the frequency domain with a 2D or 3D Log-Gabor filter. Although successful results were achieved, accurate localization is sensitive to the choice of filter parameters. The shape, orientation, and scale of the anatomical structures as well as noise in the image must be taken into account when selecting filter parameters in order to produce an optimal result.

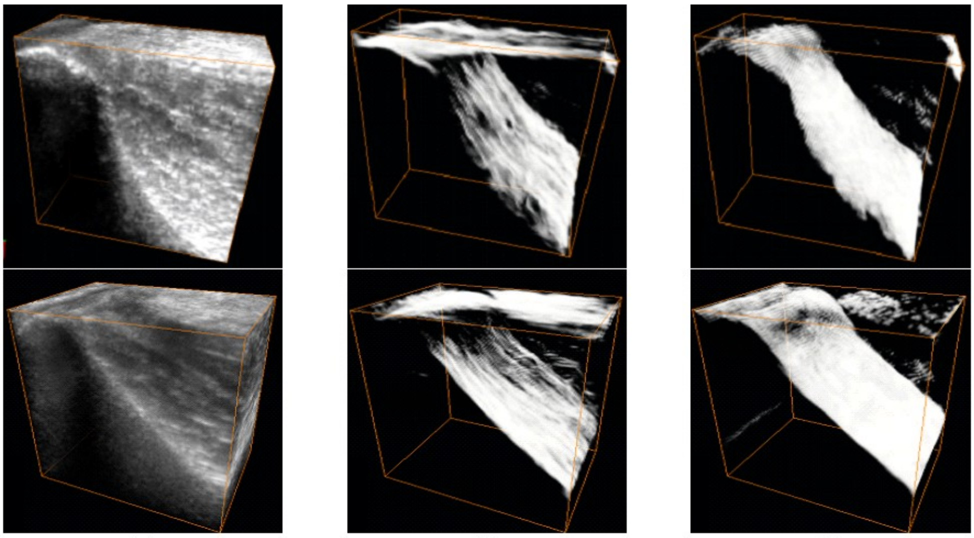
Recently, our group proposed a method of automatically selecting the scale, bandwidth and orientation parameters of 2D Log-Gabor filters in order to optimize the local phase symmetry in US images [4]. Last year [5], we showed our first clinical results using optimized 2D local phase features to extract bone surfaces from B-mode US images obtained scanning patients with pelvic ring fractures. However, as shown in our previous work in [3], 2D methods ignore the correlations between adjacent slices and are therefore subject to large spatial compounding errors as well as errors associated with the US beam thickness effects. Therefore, we have extended our previously method [4] to 3D using volume projections, surface curvature and directional filter banks within a 3D phase scale-space framework.

The objective of the current study was to determine if the proposed 3D automatic parameter selection method could produce more accurate bone segmentation results compared to the previously proposed optimized 2D method [4].We present quantitative validation results on 3D US scans obtained from trauma patients with pelvic ring fractures.

Methods: Gold standard bone surfaces were obtained from CT scans that were acquired as part of the normal clinical care from ten patients admitted to Vancouver Hospital for pelvic fractures; participating patients gave informed consent to be part of the study. The US scanning was performed either inside the operating room before the surgery or post-surgery on the ward. In the latter case, the scans were only collected from the non-fractured side to minimize discomfort to the patient. All the US scans were collected using a commercially-available real-time scanner (Voluson 730, GE Healthcare, Waukesha, WI) with a 3D RSP5-12 transducer.

The US images were then registered to the CT images using a feature-based rigid registration algorithm with manual landmarking [5].After the registration, the gold standard bone surface was using a standard thresholding approach that minimizes the intra-class variance [3].The local phase-based bone surfaces were extracted from the clinical 3D US scans using the 2D [4] and 3D optimized Log-Gabor filter parameters. For the 2D optimized method, each 2D slice of the US volume was processed to provide a 3D surface. The quality of the resulting surface matching was evaluated by computing the surface fitting error (SFE), which is defined as the root mean square distance between the two surface (CT and phase) representations [5].

Results: Figure 1 shows two 3D B-mode US scans (column (a)) obtained by scanning the patient in the region of the ilium and the corresponding phase symmetry (PS) images obtained using the 2D optimized (column (b)) and 3D optimized (column (c)) Log-Gabor filter parameters. The figure shows that the 3-D method is able to extract a connected smooth surface even when the bone surface response is weak due to shadowing from muscle and fascia interfaces above the bone surface. In contrast, the 2D [4] method is more severely affected by this overlying tissue and shows a small gap in the extracted bone surface. The average fiducial registration error was 0.31mm (SD 0.25mm). We found the SFE between the two surfaces by identifying the location of the peak intensity pixel in each vertical column of the phase-processed 3D US data set and computing the RMS distance to the thresholded surface on the registered CT image.The average SFE was 1.4 mm (SD 1.04 mm) for PS surfaces extracted using 2D optimized filter parameters and 0.51 mm (SD 0.43 mm) using the 3D optimized filter parameters.



(a) (b) (c)

Fig.1. Qualitative results for clinical validation. Column (a) 3D B-mode US volumes obtained from ilium region of the pelvis. Column (b) 3D PS bone surfaces obtained using the 2D optimized parameters (after processing individual 2-D slices of the volume). Column (c) 3D PS bone surfaces obtained using the 3D optimized filter parameters.

Discussion: In this study we have demonstrated our first clinical results of a method that extends our previous approach for optimized 2D bone segmentation in US to 3D, enabling the extraction of more accurate, smoother bone surfaces. Qualitatively and quantitatively, we have shown that integrating the surface information along the axis perpendicular to the scan plane direction makes the proposed algorithm less sensitive to soft tissue artifacts and more robust in the presence of weak bone surface responses. One of the important surgical tasks in US based computer assisted orthopaedic surgery is US-CT registration. We believe that the level of accuracy that is reported in this study is likely to provide sufficient surface information for a surface-based registration method.

References

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