FEASIBILITY OF STATISTICAL MODEL REGISTRATION TO ULTRASOUND FOR GUIDANCE IN SCAPHOID FRACTURE FIXATION

Emran Mohammad Abu Anas MSc[1], Alexander Seitel PhD[1], Abtin Rasoulian PhD[1], Paul St. John PhD[2], David Pichora PhD[2], Kathryn Darras MD[3], David Wilson PhD[4], Victoria Lessoway PhD[5], Ilker Hacihaliloglu PhD[6], Parvin Mousavi PhD[7], Robert N. Rohling PhD[1,8], Purang Abolmaesumi PhD[1*]

[1] Electrical & Computer Engineering, University of British Columbia, Vancouver, BC, Canada.

[2] Kingston General Hospital, Kingston, ON, Canada.

[3] Vancouver General Hospital, Vancouver, BC, Canada.

[4] Department of Orthopaedics and Centre for Hip Health and Mobility, University of British Columbia, BC, Canada.

[5] BC Women's Hospital, Vancouver, Vancouver, BC, Canada.

[6] Biomedical Engineering, Rutgers-The State University of New Jersey, New Jersey, USA.

[7] School of Computing, Queen's University, Kingston, ON, Canada.

[8] Mechanical Engineering, University of British Columbia, Vancouver, BC, Canada.

[*] Corresponding author.

INTRODUCTION

More than 250,000 cases of wrist injuries are reported annually in North America [Pao 2003]. There are eight carpal bones in the wrist; however, the cashew shaped scaphoid bone of approximate size of 25x10x10 mm is the most frequently (around 90%) fractured carpal bone [Mink 1999]. Primary treatment includes casting of the arm in a short arm cast, resulting in a typical healing time of 10-12 weeks, which may even be prolonged due to the disrupted blood supply to the scaphoid bone. In addition, if the fracture occurs in the proximal pole (the portion close to the radius), part of the bone might even die. Furthermore, an increased risk of arthritis develops at older ages. To avoid such complications, surgery is often recommended to fix the fracture by inserting a screw along the longitudinal axis of the scaphoid bone. Since the scaphoid width around the longitudinal axis can be as narrow as 7 mm, a strict surgical accuracy less than 2 mm is imposed [Menapace 2001]. Conventionally an open surgical approach is used to fix the fracture as it ensures accurate placement of the screw. However, it often damages the soft-tissue, destabilizes surrounding important ligaments and complicates the blood supply. To eliminate this risks, percutaneous approaches have been proposed in the literature, where a small incision is made on the palmar side of the wrist, and a screw is inserted to fix the fracture [Merrell 2008]. To guide the screw along its desired trajectory, fluoroscopy is conventionally used during the surgery. However, fluoroscopy provides only a 2D view of the complex 3D anatomy and in addition, it exposes the patient and the staff working in the operating room to harmful X-ray radiation. Ultrasound (US) has been proposed as an alternative as it allows real-time 3D data acquisition, is widely accessible, radiation free, and of comparably low cost. Since US provides only a partial view of the bony part, it should be registered to a preoperative image, e.g., CT or a statistical anatomical model to enable better interpretation of intra-operative ultrasound images.

Beek et al. [Beek 2008] proposed a solution by manually segmenting the scaphoid bone in CT and its registration to the 3D US volume using the Iterative Closest Point (ICP) algorithm. However, the manual segmentation is labour intensive and time consuming. Moreover, the 2D-3D registration is challenging due to the smooth featureless surface of the scaphoid bone. US based approaches have also been suggested in many other orthopaedic surgical applications, e.g., [Amin 2003, Kowal 2007, Penney 2006, Yan 2011]. The main difference among the above mentioned techniques lies in the detection/enhancement of the bone responses in US. It is generally fairly challenging to develop a bone response enhancement method that is insensitive to US imaging artifacts and US imaging settings. Local phase-based approaches based on the frequency spectrum of the ultrasound image were recently proposed to overcome the above mentioned challenges. Hacihaliloglu *et al.* [Hacihaliloglu 2009, Hacihaliloglu 2011, Hacihaliloglu 2012] estimated the local phase symmetry using a set of Log-Gabor filters at different scales and different orientations, where high symmetry at the bone location is utilized to enhance the bone responses. The filter design was carried out either in 2D [Hacihaliloglu 2009, Hacihaliloglu 2011] or 3D [Hacihaliloglu 2012] domain. Most recently, the Local Phase Tensor (LPT) metric was used to enhance the bony part in US image. The filters associating with this metric assumed isotropic frequency responses at all orientations, and unfortunately, this kind of filters may not be suitable to enhance the curvy bone responses.

In this work, we propose a novel solution for US-guided scaphoid fracture fixation by registration of a statistical wrist model to the bone enhanced US volume. In short, it includes (1) a novel method for enhancement of bone surfaces in US, and (2) incorporation of both shape and pose variations across the population at different wrist positions into the model used for registration. For enhancement of the bone responses in US, we exploit the local spectrum variations of the US image in order to compute the local phase symmetry. The shadow information below the bone surfaces is also used to further enhance the bone responses compared to other non-bony features. The statistical wrist model employs principal component analysis (PCA) to capture the major modes of shape and pose variations across the population, where the correspondences across the training set is established through a group-wise registration framework. The developed model is then registered to the enhanced US volume, providing the position of the scaphoid bone in the US.

METHODS

This section includes three consecutive steps: i) enhancement of bone responses from noisy US images, ii) development of the statistical wrist model, and iii) registration of the wrist model to extracted bone responses.

i) Enhancement of bone responses in US

Local phase symmetry is suggested in the literature to enhance blurry, dis-connected and noisy features in US images. A set of quadrature filters [Hacihaliloglu 2009] are used to estimate the local phase symmetry ($PS(x,y)$) as follows:

$$PS(x,y)=\frac{\sum_s\sum_o(|P_{(s,o)}(x,y)|-|Q_{(s,o)}(x,y)|-T_o)}{\sum_s\sum_o\sqrt{P^2{}_{(s,o)}(x,y)+Q^2{}_{(s,o)}(x,y)}+\in},$$

where, $P_{(s,o)}(x,y)$ and $Q_{(s,o)}(x,y)$ represent the quadrature outputs at scale s and at orientation o. $\in$ (= 0.0001) is a small constant and T_o represents the noise compensation term. The novelty in our work lies in the design of the quadrature filters. We design the filters accounting the local spectrum variations by computing the appropriate filter parameters at different orientations. It ensures proper enhancement of the US spectral energy distributed non-uniformly all over the region.

Shadow information below the bone surfaces is also utilized to further enhance the bone responses from those of other features in US. A shadow map is computed to quantify the shadow information using the idea proposed in [Foroughi 2007]. The product of the shadow map with the phase symmetry is defined as the bone response (BR) in our work, where we expect high values of bone responses only at the bone locations.

ii) Statistical model development

For development of the statistical wrist model, we have used the wrist database provided in [Moore 2007]. The dataset contains 3D surface models of all carpal bones of 30 subjects (both arms) at neutral positions. In addition, it provides rigid body transformations for each carpal bone to map it from neutral to different non-neutral wrist positions. The model development starts with establishing the correspondences across the shapes of the carpal bones at neutral positions using a group-wise registration framework. The mean shape is generated using Procrustes analysis, and the shape statistics is developed based on the idea presented in [Bossa 2007]. We have also used their idea to develop the pose statistics, however, two different pose models are generated in our work. The 'Inter' pose model represents the pose variations across the population at a fixed wrist position, and the 'intra' pose model captures the variations across different wrist positions over a same individual.

iii) Registration of statistical model to enhanced bone surfaces

A probabilistic approach is used to register the wrist model to the enhanced bone surfaces in US [Rasoulian 2013]. Thresholding is performed on the bone response images to extract the partial bone surfaces. To initialize the wrist model close to the target wrist surface, some corresponding landmarks are selected from these surfaces. Finally, an Expectation Maximization (EM) technique is utilized to estimate the model coefficient for the probabilistic registration.

RESULTS

3D US volumes are acquired from both arms of two volunteers at two different wrist positions. For US data acquisition, a motorized transducer (Ultrasonix 4D L14-5/38) with a centre frequency of 10 MHz is used. The position of the US transducer on a left wrist is shown in Fig. 1(a). Fig. 1(b) shows the overlay of the registered wrist model to a volume rendering of US volume acquired from the first volunteer.

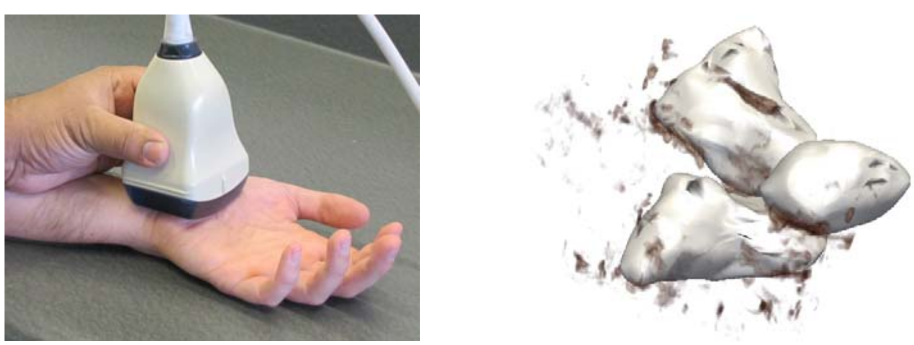

Figure 1: Wrist scanning procedure. (a) Position of the US transducer on the wrist. (b) Overlay of registered wrist model to volume rendering of US volume acquired from the first volunteer.

DISCUSSION AND CONCLUSIONS

We have presented a novel approach for enhancing 3D US volumes of the wrist by integrating 3D intraoperative US with a statistical wrist model. The key contribution is the enhancement of bone responses in US exploiting local spectrum variations, and the development of a statistical wrist model capturing major modes of shape and pose variations across the population at different wrist positions. We have performed feasibility experiments using *in vivo* wrist data. The result in Fig. 1(b) indicates a promising performance of the proposed approach. A key difference of our method with most of the previous techniques (e.g., [Amin 2003, Kowal 2007, Penney 2006, Yan 2011, Hacihaliloglu 2009]) that we exploit both intensity (spatial domain) and symmetry (frequency domain) information to enhance the bony surfaces, whereas they use information of either one domain.

Future work involves a more extended study on further *in vivo* data and the development of an automatic initialization that is able to initially position the wrist model roughly at the right position in the enhanced US volume before the model-based registration is performed. For use in a typical clinical work flow, the run-time, which is currently within several minutes, needs to be substantially reduced. Efficient parallel implementation can be applied to both the bone enhancement and the registration algorithm. Finally, the results from the feasibility experiments demonstrate the potential of the proposed technique to further develop accurate anatomy localization for guiding percutaneous scaphoid fracture fixations.

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ACKNOWLEDGEMENT

We would like to thank the Natural Sciences and Engineering Research Council (NSERC), and the Canadian Institutes of Health Research (CIHR) for funding this project.