Freehand 3-D Sonographic Measurement of the Superficial Femoral Artery

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Abstract. Visualization of vessels for diagnostics and intervention are usually done under fluoroscopic X-ray view using intravenous contrast agents, which has potential risks. To avoid this problem an ultrasound-based approach was investigated. The definition of reproducible geometric measures is important for image guided navigated implantations. Such measures can benefit from geometric body which approximate the vessels. We addressed the problem of fitting cylindric bodies to datasets by using a robust technique based on rejection strategies for irrelevant points and data sets.

1 Introduction

Generally catheterizations of vessels are made for findings of vascular diseases like vascular obliteration. Depending on whether vascular diseases are detected, balloon angioplasty or stent implantations are performed. Diagnostics and intervention are done under fluoroscopic X-ray view using intravenous contrast agents. Contraindications for the use of intravenous contrast agents are known allergic reaction, nephropathy or hyperthyreosis. However, 2-D sonography and especial Doppler sonography have already proven to visualize the vessel system sufficiently during an intervention [1, 2], avoid X-ray exposure as well as contrast agent application and this can be valuable alternative.

Three-dimensional ultrasound (3-D US) imaging techniques are already established for intra-operativ registration [3] and organ detection [4]. Since optical tracking system having line of sight problems the use of electromagnetic tracking devices for freehand 3-D US volume acquisition seems to be the best choice for this application even though position data have to be checked carefully [5, 6]. Especially, due to the absence of ultrasonic visible markers for identifying the length of balloon catheters and stent devices is problematic. In this pilot study, we investigated the problem of fitting geometric bodies to 3-D US image volumes of the femoral artery and the measurement of its geometry.

2 Materials and Methods

Three-dimensional ultrasound image volumes of the femoral artery of four patients with vascular diseases were acquired. For this purpose, a high-class conventional ultrasound imaging system (iU 22, Philips Medical Systems, Bothell, USA) with a linear 4-8 MHz probe was used together with an electro-magnetic localizer system (Aurora™, Northern Digital Inc., Waterloo, Ontario, Canada). Two six degrees-of-freedom sensors are attached to the transducer to locate the ultrasound probe position and to detect non-conformable position data. The sensor positions are recorded synchronously with 2-D ultrasound images during manually performed freehand sweeps (Fig. 1). The sweeps of the same anatomical structures are recorded several times to control the influence of small patient movements and possible investigator induced tissue deformations during data acquisition.

After recording of the image and position data, the 2-D images are segmented automatically. The segmentation process takes advantage of the colored Doppler data in the 2-D images and heuristics on anatomic plausibility of the vessel's continuity. Table 1 describes the segmentation algorithm in detail. The indices (a-d) correspond to the result-images in Fig. 2.

The segmentation results (Table 1) are scattered data from the structure's surface at voxel position $\mathbf{x}_{\text{volume}}$. Among the visual examination, for navigated intervention geometrically interpretation of segmented objects are necessary. To quantify the shape of the segmentation results and to remove erroneous data, cylindric bodies can be adapted, so that they fit to the data better than a small error ϵ. Since the points are in general considerably corrupted by segmentation and position measurement errors, the identification of the cylindric body's parameters is inherently instable. In this work we used an iterative approach to generate a robust, i.e. data insensitive identification. The robustification consists of the computation of cylindric reference bodies and the iterative discard of possible erroneous voxels. In this approach, we use a cylinder model for approximation of parts of the femoral artery system.

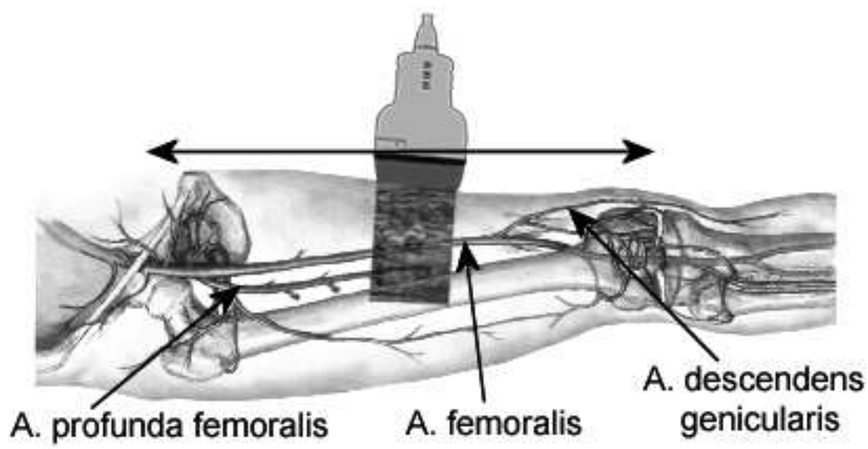

Fig. 1. Acquiring 3-D US image volumes of the femoral artery, modified from [7]

Table 1. Processing steps of automatic vessel detection

index	description
a	preprocessing: Enhance image contrast by using histogram stretching; noise reduction by using image despeckling
b	Detect circular Doppler data with radius between 20 and 60 pixels; outline the regions
c	After detecting the Doppler data border, a region growing algorithm is used to expand the segmentation to the artery wall
d	Transfer the segmentation results to images without Doppler data by using a heuristic estimation about artery geometry

N voxels $\mathbf{x}_{\text{volume}}(i),\ i = 1, \ldots, N$ of the entire volume may approximate a cylinder jacket which is characterized by the cylinder-axis vector $\mathbf{x}_C$, the position vector $\mathbf{x}_0$ and the radius R of the cylinder. A least-squares-fit must be determined, such that the error of estimation is to be minimized. The optimum is found by discarding $\alpha\%$ of all N voxels and minimization of the functional $J(\Theta, \mathbf{x}_{\text{volume}})$ over the remaining voxels $j = 1, \cdots, N \cdot (1 - \alpha)$ by an appropriate choice of the parameters $\Theta = (\mathbf{x}_C, \mathbf{x}_0, r)$.

$$J\left(\Theta, \mathbf{x}_{\text{volume}}\right) = \sum_{j=1}^{N\cdot(1-\alpha)} \left(\frac{|\mathbf{x}_C \times (\mathbf{x}_{\text{volume}}(j) - \mathbf{x}_0)|}{|\mathbf{x}_C|} - R \right)^2 = \sum_{j=1}^{N\cdot(1-\alpha)} e_j^2 \rightarrow \min$$

The algorithm is initialized by a principal component analysis (PCA) of all N voxels. Their center point $\mathbf{x}_{center}$ is a starting gues for $\mathbf{x}_0$. The eigenvector belonging to the largest eigenvalue gives the initial value for $\mathbf{x}_C$.

The following steps are processed:

- determine initial values $\mathbf{x}_0$ and $\mathbf{x}_C$ from PCA, $(\alpha = 0, j = 1 \cdots, N)$
- discard randomly $\alpha\%$ of all N voxels $(j = 1 \cdots, N \cdot (1 - \alpha))$

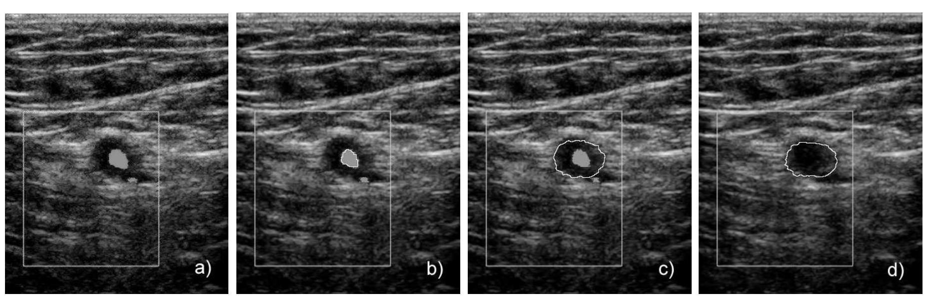

Fig. 2. Image segmentation (intermediary results): a) original ultrasound image, b) detect Doppler data, c) expand to artery wall, d) transfer to images without Doppler data

– find the best fit for all $N \cdot (1-\alpha)$ remaining voxels by using Nelder-Mead-Simplex optimization [8]. If the minimization criterion of the numerical optimization algorithm is fulfilled [8], go to step 3, else generate new parameters $\mathbf{x}_0$ and $\mathbf{x}_C$, set $\alpha > 0$ and go to step (1)
– $\mathbf{x}_0, \mathbf{x}_C$ and R are the optimal cylinder parameters, J is a measure for the accuracy of the fit.

If the optimal cylinder parameters are found, the algorithm receives a new sample of N voxels from the volume.

To verify the approximation algorithm, corrupted datasets of β% of all segmented voxels where added to a manually corrected 3-D ultrasound volume. The corrupted datasets contain a set of normally distributed erroneous points $\mathbf{x}_{\text{noise}}$ over the entire volume.

3 Results

Image acquisition of all sweeps took less than 10 minutes for each patient. By positioning the patient in a stable supine position, the course of the A. iliaca externa, their bifurcation into A. femoralis and A. profunda femoralis as well as the bifurcation of the A. femoralis into the A. descendens genicularis can be recorded. The visualization of all US image sweeps of one patient showed slightly deformed and translated vessel shapes with a maximum deviation of 4 mm. The minimal diameter of automatically detected vessels by approximating with the cylinder model was 3 mm. The approximation algorithm is able to detect cylindrical vessels, adding up to $\beta = 5\%$ of noise (Fig. 3a) to the segmented ultrasound volume. The result are shown in Fig. 3c).

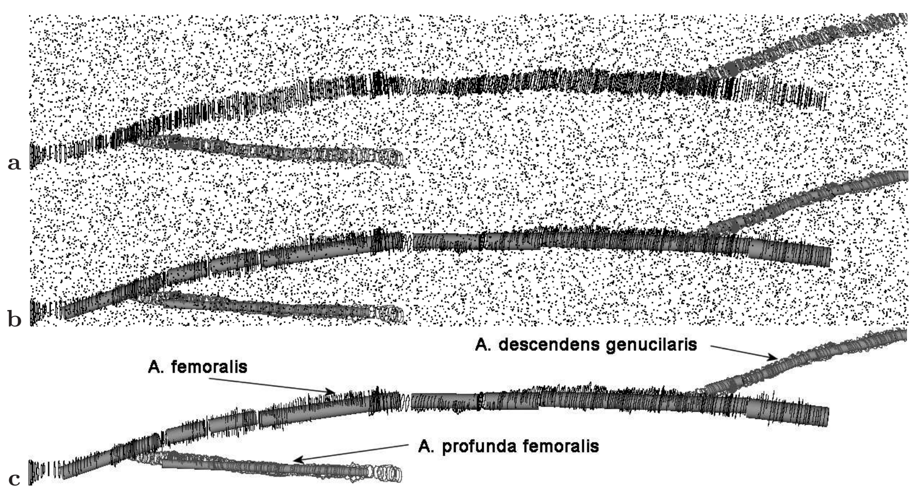

Fig. 3. Results of the approximation with the cylinder model by adding 5% noise to the data

4 Discussion

The presentability of the femoral artery in 3-D ultrasound volumes has proven to be quite successful. The vessel's geometries in two different US image volumes is reproducible up to 4 mm and can not be separated to image presentation under different acquisition orientations, segmentation errors or wanting patient fixation.The approach to define simple geometric bodies and to approximate them using data-robust algorithms seems to be applicable also for other anatomical structures and leads directly to a more robust image segmentation procedure.

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