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Hybrid constraint optimization for 3D subcutaneous vein reconstruction by near-infrared images

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A R T I C L E I N F O

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Background and objective: The development of biometric identification technology and intelligent medication has enabled researchers to analyze subcutaneous veins from near-infrared images. However, the stereo reconstruction of subcutaneous veins has not been well studied, and the results are difficult to utilize in clinical practice.
Methods: We present a hybrid constraint optimization (HCO) matching algorithm for vein reconstruction to solve the matching failure problems caused by the incomplete segmentation of vein structures captured from different views. This algorithm initially introduces the existence of the epipolar and homography constraints in the subcutaneous vein matching. Then, the HCO matching algorithm of the vascular centerline is established by homography point-to-point matching, homography matrix optimization, and vascular section matching. Finally, the 3D subcutaneous vein is reconstructed on the basis of the principle of triangulation and system calibration parameters.
Results: To validate the performance of the proposed matching method, we designed a series of experiments to evaluate the effectiveness of the hybrid constraint optimization method. The experiments were performed on simulated and real datasets. 42 real vascular images were analyzed on the basis of different matching strategies. Experimental result shows that the matching accuracy increased significantly with the proposed optimization matching method. To calculate the reconstruction accuracy, we reconstructed seven simulated cardboards and measured 10 vascular distances in each simulated cardboard. The average vascular distance error of each simulated image was within 1.0 mm, and the distance errors of 75% feature points were less than 1.5 mm. Also, we printed a 3D simulated vein model to improve the illustration of this system. The reconstruction error extends from −3.58 mm to 1.94 mm with a standard deviation of 0.68 mm and a mean of 0.07 mm.
Conclusions: The algorithm is validated in terms of homography optimization, matching efficiency, and simulated vascular reconstruction error. The experimental results demonstrate that the veins captured from the left and right views can be accurately matched through the proposed algorithm.

1. Introduction

In modern medicine, intravenous injection is commonly administered in clinical nursing work as it plays an important role in treatment, rehabilitation, and medical care. In the United States, approximately one billion intravenous injections are performed every year. The first-injection failure rate for adult patients is as high as 28% and even higher for children and special-disease patients [1]. Injection failure may be due to skin color, skin damage, skin aging, obesity, and thin blood vessels. Repeated injection causes not only trauma and pain, but also venous sclerosis. For young patients, these consequences may result in long-term mental and psychological trauma [2]. To improve the success rate of first-time intravenous injection, researchers have further developed assistive equipment for intravenous injection.

The venous blood component possesses strong light-absorption characteristics within the spectral range of 700–900 nm. Active near-infrared imaging technique is the main imaging method for subcutaneous veins. Early studies on subcutaneous veins have

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mainly focused on the enhancement, segmentation, and feature extraction of single near-infrared vein images. Juric et al. [3] proposed a low-cost mobile health solution for subcutaneous vein detection using near-infrared spectroscopy, which can enhance subcutaneous vein images in real time. With the development of robot and computer vision technologies, 3D structure and depth analysis for subcutaneous veins have significantly progressed in recent years. Nakamachi et al. [4,5] designed a 3D finger vein-tracking and blood-sampling system. This system performs finger vein stereo matching and depth reconstruction according to the matching information on the luminance distribution along the horizontal direction. A similar system developed by Brewer and Salisbury [2] extracted the vascular bifurcation in near-infrared images by using circular neighboring analysis and calculated the spatial location and injection angle of the bifurcation with epipolar constraint. Meriaudeau et al. [6] designed a complete vision system to detect multispectral and 3D information of the arm surface, which is useful for automatic needle insertion for robotic system. By performing edge extraction and sum of absolute differences matching, Zhang et al. [7] accurately extracted the subcutaneous vein image and identified 3D vein features through intravenous point matching. Fernández and Armada [8] proposed a multisensory system for detecting and locating peripheral subcutaneous veins, which accurately mapped the subcutaneous veins onto the 3D reconstructed surface. To date, the stereo reconstruction of subcutaneous veins has not been well studied, and the results are difficult to utilize in clinical practice.

However, similar stereo reconstruction technologies for the coronary artery have been widely studied in the past two decades. Generally, coronary artery reconstruction is achieved through bottom-up and top-down methods after matching branches. On the basis of the segmentation results in the known vascular view, 3D vascular structure can be reconstructed through a bottom-up method by which vascular matching relationships among different viewpoints are searched. Dorsaz et al. [9] performed semi-automatic matching by vascular epipolar constraint and then optimized vascular structures by minimizing back-projective functions. Meanwhile, Zifan et al. [10] used the genetic algorithm to reconstruct the vascular centerline with high precision by optimizing the point-to-point matching between different views. Cong et al. [11] utilized the extra information to extend the previous external force back-projective composition model (EFBPCM) to multiple angiographic images at different angles. Liao et al. [12] improved the accuracy of vascular matching by modifying the epipolar constraint condition and optimized the structure of the energy function constructed by the smoothness constraints and epipolar constraints based on the graph cut.

In contrast, the top-down methods first define the parameter model and the deforming energy function of the vascular structure. The parameter model is then optimized on the basis of the energy function to achieve the projection matching of all views. For such methods, the most widely used model is the snake structure, in which the energy function consists of both internal and external energy fields. The internal energy ensures the tension and stiffness of the parameterized curve, whereas the external energy reflects the driving force of the intensity distribution of the image. Given these two energy fields, the parameterized curve evolves continuously to approach the target curve. When these curves coincide, minimum results for the energy function are obtained. Molina et al. [13] first proposed the snake model to 3D reconstruct vessels; the snake model minimizes the projection errors of the snake curve in each view with respect to the vessel segment distance. Canero et al. [14] modified the external energy field of the snake model through generalized vector flow, which improved the accuracy of reconstruction results for major vascular branches. Sun et al. [15] and Yang et al. [16,17] combined heart fluctuation error and 3D synthetic error in the energy field and consequently achieved a more accurate vascular reconstruction.

The near-infrared subcutaneous vein image is more difficult to reconstruct than an angiographic image. First, the near-infrared image cannot highlight the texture features of vessels that lack color information [18,19]. Second, the contrast between veins and the skin in near-infrared images is much lower than that in angiographic images with injected contrast agent [20]. Third, the near-infrared imaging requires an infrared light source to amplify the vein response [21]. Hence, when the light intensity is uneven or illumination angle is tilted, substantial noise may be induced in the image. To solve these problems, our previous work [22] introduced the segmentation method for extracting vascular vein structures from near-infrared images based on multiple feature classification. And, we proposed a 3D reconstruction and fast imaging system based on augmented reality technology. The system consists of five main devices, including two industrial cameras, a color micro-project, a set of NIR LED rings, and a workstation with custom-designed software for vein segmentation, vein construction, and skin construction [23].

This study presents a hybrid constraint optimization matching algorithm for 3D reconstruction of subcutaneous veins that captured in different views. For this study, the epipolar and homography constraints are introduced for accurate vein matching, which is named as hybrid constraint optimization (HCO). The HCO matching algorithm of the vascular centerline is established by homography point-to-point matching, homography matrix optimization, and vascular section matching. Based on the estimated imaging parameters of the binocular system, the bottom-up vascular reconstruction is achieved through the principle of triangulation measurement. The major contributions of our study are as follows: first, a subcutaneous vein matching method is proposed to match the centerline of vascular branches from two images that captured in different views. It can be applied to identify the spatial structure of subcutaneous veins. Second, as the vein distribution of hand-back is mostly approximate to a plane, the epipolar and homography constraints are introduced for the matching process. Hence, it can considerably improve the matching efficiency. Third, three optimization strategies, including homography point-to-point matching, homography matrix optimization, and vascular section matching are introduced for the calculation, which can effectively increase the matching accuracy.

2. Methodology

2.1. Epipolar constraint

The epipolar constraint is an important principle in computer vision commonly used for the definition of matching relationships among images obtained at different views. However, numerous vascular structures in stereo reconstructed veins are mismatched with different binocular imaging angles. Fig. 1 demonstrates six possible intersection cases as follows:

P_a: no intersection point between epipolar line and centerline;
$P_b \leftrightarrow P'_b$: one intersection point between epipolar line and centerline matched correctly;
$P_c \leftrightarrow P'_c$: one intersection point between epipolar line and centerline matched incorrectly;
$P_d \leftrightarrow P'_d, P''_d$: multiple intersection points between epipolar line and multi-centerlines, with some correctly matched points;
$P_e \leftrightarrow P'_e, P''_e$: multiple intersection points between epipolar line and multi-centerlines, but without correctly matched points;
P_f: multiple intersection points between epipolar line and one centerline nearly parallel to one another.