Proceedings of the 28th IEEE
EMBS Annual International Conference
New York City, USA, Aug 30-Sept 3, 2006

A Non-Rigid Image Registration Technique for 3D Ultrasound Carotid Images using a "Twisting and Bending" Model

N.D. Nanayakkara, B. Chiu, A. Samani, J.D. Spence, J. Samarabandu, and A. Fenster

Abstract— **Atherosclerosis at the carotid bifurcation resulting in cerebral emboli is a major cause of ischemic stroke. Most strokes associated with carotid atherosclerosis can be prevented by lifestyle/dietary changes and pharmacological treatments if identified early by monitoring carotid plaque changes. Sensitive monitoring of plaque changes in volume and morphology requires that 3D ultrasound (US) images of carotid plaque obtained at different time points be registered and evaluated for change. This registration technique should be non-rigid, since different head positions in image acquisitions cause relative bending and torsion in the neck, producing non-linear deformations between the images. We modeled the movement of the neck using a "twisting and bending model" with only six parameters for non-rigid registration. We used a Mutual Information (MI) based image similarity measure with the Powell optimization method as they have been used effectively in US image registration applications. For evaluation of our algorithm, we acquired 3D US carotid images from three subjects at two different head positions to simulate images acquired at different times. Then, we registered each image set using our "twisting bending model" based non-rigid registration algorithm. We calculated the Mean Registration Error (MRE) between the segmented vessel surfaces in the target image and the registered image using a distance-based error metric. We repeated the experiment with only rigid registration to compare the capabilities of the proposed algorithm in improving registration of 3D carotid US images. The average registration error was 1.03 ± 0.23mm using our non-rigid registration technique, while it was 1.50 ± 0.50mm when we applied the rigid registration alone.**

I. INTRODUCTION

Stroke is the fourth leading cause of death in Canada [1], and third leading cause of death in USA [2], and the leading cause of serious, long-term disability in North America. Clearly stroke represents a staggering mortality, morbidity, and economic cost. About 85% of strokes are ischemic, i.e. due to the blockage of a cerebral artery or arteriole. Atherosclerosis at the carotid bifurcation is a major cause of occlusion or cerebral emboli [3]. Most strokes associated with carotid atherosclerosis can be prevented by lifestyle/dietary changes and pharmacologic treatments if identified early [4]. Application of non-invasive ultrasound US imaging techniques for early identification of vulnerable plaques and for monitoring of plaque changes is an active research area. Carotid plaque monitoring is currently limited to measurement of change in plaque volume, area, or wall thickness [5]. However, research showed that sensitive monitoring of plaque surface morphology is required for effective identification of vulnerable plaques to prevent strokes [6]. Sensitive monitoring of plaque changes in surface morphology requires that 3D US images of carotid plaque obtained at different times be registered. The registration technique is required to be non-rigid, since the patient's head positions can be different in each image acquisition session causing relative bending and twisting of the carotid artery in each image.

Registration of carotid images has only been reported a few times in the literature. Slomka *et al.* reported the first 3D rigid registration algorithm for carotid images, where they used MI to register 3D Magnetic Resonance Angiography (MRA) images with Power Doppler US (and indirectly with 3D US) [7]. Fei *et al.* reported an automatic rigid registration algorithm for multiple contrast weighted MR images of carotid vessels [8]. More recently, Chan *et al.* reported the first non-rigid registration algorithm in 3D carotid image registration, in which they applied the thin-plate-spline based deformable registration to carotid MR and 3D US datasets and observed mean registration errors on the order of 1 mm when tested *ex vivo* [9]. The deformable registration method such as the algorithm reported by Chan *et al.* or elastic image registration used in nonrigid registration of US used in elsewhere [10] are not always suitable in monitoring carotid plaque changes since they can alter the existing plaque morphology during registration process.

This paper presents a nonrigid registration algorithm for registration of 3D US images of carotid artery taken at two different times. We modeled the possible movements of the neck using a biomechanical model to avoid plaque morphology alteration during the registration. We used the MI as the image similarity measure with this algorithm since it has been successfully used in US image registration [12], [13]. We used a distance based error metric between

N.D. Nanayakkara is with Imaging Research Laboratories, Robarts Research Institute and Graduate Program in Biomedical Engineering, The University of Western Ontario, London, Ontario, Canada nnanayak@uwo.ca

B. Chiu is with Imaging Research Laboratories, Robarts Research Institute and Graduate Program in Biomedical Engineering, The University of Western Ontario, London, Ontario, Canada bchiu@imaging.robarts.ca

A. Samani is with Department of Medical Biophysics and Graduate Program in Biomedical Engineering, The University of Western Ontario, London, Ontario, Canada asamani@uwo.ca

J.D. Spence is with Departments of Neurology and Clinical Pharmacology, The University of Western Ontario and Stroke Prevention & Atherosclerosis Research Centre, Robarts Research Institute, London, Ontario, Canada dspence@robarts.ca

J. Samarabandu is with Department of Electrical & Computer Engineering, The University of Western Ontario, London, Ontario, Canada jagath@uwo.ca

A. Fenster is with Imaging Research Laboratories, Robarts Research Institute and Graduate Program in Biomedical Engineering, The University of Western Ontario, London, Ontario, Canada afenster@imaging.robarts.ca

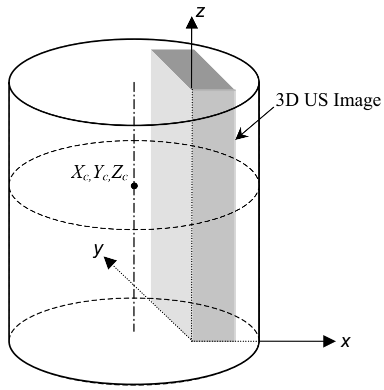

Fig. 1. The Twisting and Bending model assumes that the 3D ultrasound carotid image is a part of a cylindrical shaft. The model parameters (X_c, Y_c, Z_c) defines the "twist-bend center", which does not move during the deformation.

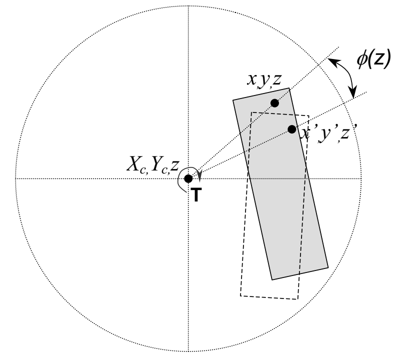

Fig. 2. The twisting model: a plane perpendicular to z-axes showing the twisting

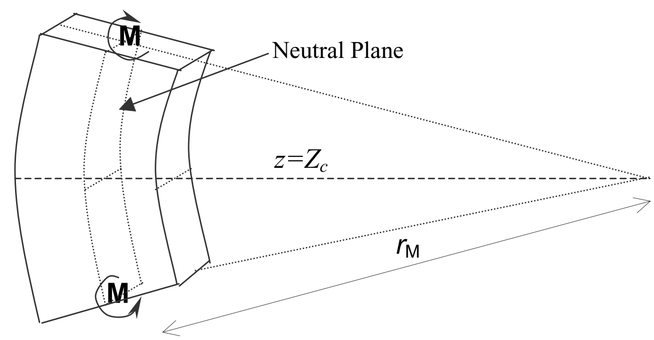

Fig. 3. The bending model: the height of the neutral plane does not change during bending

segmented vessel surfaces defining a novel distance measurement technique to test the accuracy of the proposed algorithm using *in vivo* 3D carotid US images.

II. Methods

Non-rigid image registration is a valuable tool for various medical imaging applications. The large number of parameters associated with existing methods cause several problems in registration including computational complexity, long computation time, and low reliability [14]. However, movements of the neck are mainly limited to bending and twisting, and can therefore be modeled by a reasonably low number of parameters. We modeled the movement of the neck using a biomechanical "twisting and bending model" with only *six* parameters for non-rigid registration of carotid US images. Our non-rigid registration algorithm consists of two parts, rigid registration for rotation and translation combined with non-rigid registration for twisting and bending. We used Mutual Information (MI) for the image similarity metric due to its favourable performances on US images [13]. We used Powell optimization [15] as it is well suited for non-rigid US image registration applications, since it does not require gradient calculations to search for optimal solution [16].

A. Twisting and Bending Model

The Twisting and Bending model assumes that the 3D US carotid image is part of a homogeneous cylindrical shaft as shown in Figure 1. The central axes of the common carotid, which passes through the user defined bifurcation position, should be approximately aligned parallel to the z-axes as a pre-processing step. The *three* model parameters (X_c, Y_c, Z_c), the "twist-bend center", define the center of the model, which does not move during the deformation. Kinematic modeling of head and neck movements have been performed for robotic and control system applications [17]. Generally the neck has a multiple rotation centers, but Ouerflli *et al.* modeled 3D neck movements using a three-revolute-joint system [17]. In our case, the range of deformations in 3D US images is limited to small region of all possible neck movements and can be assumed to have a single joint (or center).

The twisting model assumes that the shaft is clamped at the bottom plane of the z-axes (at $z = 0$), and the twisting is defined by one parameter, Torsion, $\mathbf{T}$. Each plane normal to the z-axes at $z = z$, rotates around the axes with a different angle as described in equation 1 and shown in Figure 2. Any plane perpendicular to the twisting axis is not distorted under the homogeneous cylindrical shaft assumption [18]. The bending model assumes a pure bending condition under equal and opposite bending moments, $\mathbf{M}$, acting at the two ends of the z-axes [18]. The bending model has two parameters defining the two components, M_x and M_y, of the bending moment $\mathbf{M}$, in the two directions x and y respectively. These parameters define the curvature ($\frac{1}{r_M}$) as shown in the Figure 2, and are described in equation 2.

$$\phi(z) \propto |\mathbf{T}|z \tag{1}$$

$$\frac{1}{r_M} \propto |\mathbf{M}| \tag{2}$$

B. Registration

The registration process was defined as a numerical optimization technique, where the Powell optimizer [15] finds the best combination of *six* rigid parameters (3 rotations and 3 translations) and *six* twisting and bending model parameters

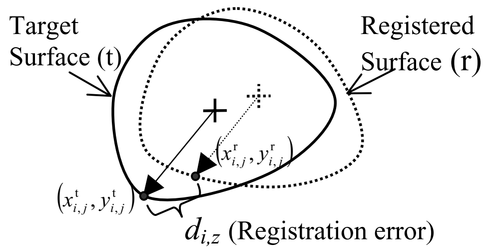

Fig. 4. Registration error calculation using the distance between corresponding points on the target $(x^t_{i,z}, y^t_{i,z})$ and registered $(x^r_{i,z}, y^r_{i,z})$ images on each plane normal to z-axes at every 1mm.

$(|\mathbf{T}|, M_x, M_y, X_c, Y_c, Z_c)$ that maximizes the MI between the target and the source 3D US carotid images.

C. Evaluation

We acquired *six* sets of 3D US carotid images from *three* subjects at different head positions: head straight, and bent back & twisted to the side, to simulate images acquired at different times. Carotid US scans were performed at the Imaging Research Laboratories, Robarts Research Institute, using a Philips/ATL HDI 5000 US machine (Philips/ATL). An L125 probe with a central frequency of 8.5 MHz was used in the composite imaging (SonoCT) mode. The probe was attached to a motorized linear mover driven by a Life Imaging Systems L3Di 3D US acquisition system (Life Imaging Systems) [19]. Then, we registered the two images using our twisting bending model based non-rigid registration algorithm. We calculated the Mean Registration Error (MRE) between the segmented vessel surfaces in the target image and the registered image using a distance-based error metric described below in this section. We repeated the experiment with only rigid registration to compare the capabilities of the proposed algorithm in improving the registration of 3D US images of the carotid artery.

We developed a distance-based error metric to evaluate the registration accuracy as shown in Figure 4. The mean distance between the two surfaces was calculated by averaging the distances, $d_{i,j}$ (equation 3) between corresponding points, $(x^t_{i,j}, y^t_{i,j})$ on the target and $(x^r_{i,j}, y^r_{i,j})$ on the registered surfaces on each plane normal to z-axes at 1mm interval.

$$d_{i,j} = \|(x^t_{i,j}, y^t_{i,j}) - (x^r_{i,j}, y^r_{i,j})\| \tag{3}$$

We defined the corresponding points by projecting lines, i from each centre to the surface at the same angle every 4^o. Then, the mean registration error (MRE) was calculated thus:

$$\text{MRE} = \frac{1}{N}\sum_{j=1}^{N}\left[\frac{1}{M_j}\sum_{i=1}^{M_j} d_{i,j}\right] \tag{4}$$

where, M_j is the total number of points in each plane j, and N is the total number of planes perpendicular to the z-axis.

III. Results

We registered *six* sets of 3D carotid US images of *three* subjects using the proposed "twisting and bending model" based non-rigid registration algorithm and repeated the process using only the rigid registration approach. Figure 5 shows an example of one image set depicting the improvement achieved by our non-rigid registration algorithm over the rigid registration. Figures 5(a) and 5(c) show the segmented carotid artery surfaces after registration using the respective methods, and Figures 5(b) and 5(d) show the distance-based error metric calculated and mapped onto the surface at every point on the vessel boundary in the target image.

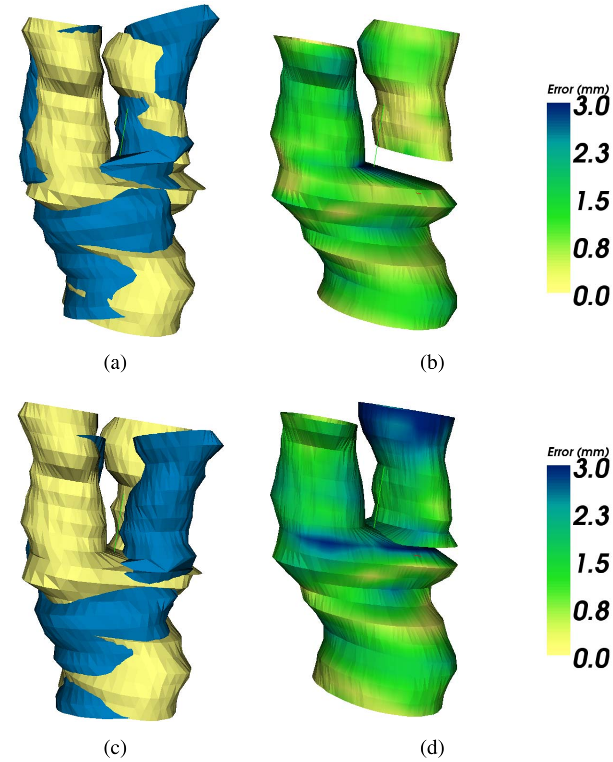

Fig. 5. Registration results, (a) vessel boundaries after "twisting and bending" model based non-rigid registration, (b) distance (mm) between two surfaces, (c) vessel boundaries after only rigid registration, and (d) distance (mm) between two surface.

The error metric values for the "twisting and bending" biomechanical model based non-rigid registration and rigid registration are tabulated in Table. I. The registration error has been reduced in every image set when using non-rigid registration over the rigid registration. The average distance between the two carotid artery surfaces was reduced to 1.03 ± 0.23mm when using our non-rigid carotid image registration technique.

IV. Conclusions

Effective monitoring of carotid plaque changes using non-invasive US imaging techniques is important for assessing carotid disease progression and regression of patients at risk for stroke and in response to therapy. The inevitable variability of head position in each image acquisition session makes it very difficult to measure plaque changes in surface morphology and composition in images acquired at different time points. This difficulty has been encountered

TABLE I

DISTANCE-BASED MEAN REGISTRATION ERROR (MRE) FOR BOTH "TWISTING AND BENDING" BIOMECHANICAL MODEL BASED NON-RIGID REGISTRATION AND RIGID REGISTRATION. THE LAST ROW SHOWS THE MEAN (AND STANDARD DEVIATION IN PARENTHESIS) FOR BOTH CASES.

Image Set	**MRE** *(mm)*	
	Non-Rigid	**Rigid**
Subject 1 - Left	1.42	2.44
Subject 1 - Right	0.95	1.66
Subject 2 - Left	1.02	1.22
Subject 2 - Right	1.10	1.30
Subject 3 - Left	0.74	1.12
Subject 3 - Right	0.96	1.28
Overall Mean (SD)	1.03 (0.23)	1.50 (0.50)

not only with different imaging modalities but also within a single modality. Rigid registration techniques do not align these images effectively due to the non-linear nature of the relative deformations between these images. The non-rigid registration techniques developed for other registration application had several drawbacks due to the large number of parameters involved in the registration. We developed a "twisting and bending" biomechanical model based image registration technique by successfully limiting the number of parameters to just *six* to overcome the limitations associated with existing non-rigid registration techniques. We also developed a distance based error metric to evaluate the accuracy of our registration algorithm.

We applied our algorithm to *six* sets of US images acquired at different head positions of *three* subjects. The average registration error was 1.03 ± 0.23mm using our non-rigid registration technique, while it was 1.50 ± 0.50mm when we applied the rigid registration alone. Visual inspection of segmented vessel surfaces also showed a substantial improvement of alignment with our non-rigid registration technique.

Currently, we are optimizing the various parameters in the registration process to increase the registration accuracy and efficiency. We are also analyzing the effects of vessel boundary segmentation error in evaluation of registration accuracy. Furthermore, we are extending this algorithm to register US images with 3D Magnetic Resonance (MR) images for monitoring changes in plaque composition.

We believe that our "twisting and bending" biomechanical model based non-rigid registration technique will improve the management of patients at risk for stroke and ultimately reduce the number of strokes.

ACKNOWLEDGMENTS

The authors wish to thank Chris Blake for his work in image acquisition. This work has been supported by the Canadian Institutes for Health Research (CIHR), The Ontario R&D Challenge Fund, The Richard Ivey Foundation and Ontario Graduate Scholarship program. A. Fenster holds a Canada Research Chair and acknowledges The Canada Research Chair Program.

REFERENCES

[1] "Stroke statistics," The Heart and Stroke Foundation of Canada. [Online]. Available: http://www.heartandstroke.ca

[2] "Stroke facts and statistics," Centers for Disease Control and Prevention, Atlanta, GA, USA, 2006. [Online]. Available: http://www.cdc.gov/stroke

[3] B. M. Eicke, J. von Lorentz, and W. Paulus, "Embolus detection in different degrees of carotid disease," *Neurol. Res.*, vol. 17, no. 3, pp. 181–184, 1995.

[4] "Changing face of heart disease and stroke in canada 2000," The Heart and Stroke Foundation of Canada, Oct. 1999. [Online]. Available: http://www.heartandstroke.ca

[5] A. Landry, J. D. Spence, and A. Fenster, "Measurement of carotid plaque volume by 3-dimensional ultrasound," *Stroke*, vol. 35, no. 4, pp. 864–869, Apr. 2004.

[6] T. S. Hatsukami, M. S. Ferguson, K. W. Beach, D. Gordon, P. Detmer, D. Burns, C. Alpers, and D. E. Strandness Jr, "Carotid plaque morphology and clinical events," *Stroke*, vol. 28, no. 1, pp. 95–100, Jan. 1997.

[7] P. J. Slomka, J. Mandel, D. Downey, and A. Fenster, "Evaluation of voxel-based registration of 3-d power doppler ultrasound and 3-d magnetic resonance angiographic images of carotid arteries," *Ultrasound in Medicine & Biology*, vol. 27, no. 7, pp. 945–955, July 2001.

[8] B. Fei, S. Zhang, O. Savado, J. Suri, J. S. Lewin, and D. L. Wilson, "Three-dimensional automatic volume registration of carotid mr images," in *Proceedings of the 25th Annual International Conference*, vol. 1. IEEE Engineering in Medicine and Biology Society, Sept. 2003, pp. 646–648.

[9] R. C. Chan, S. Sokka, D. Hinton, S. Houser, R. Manzke, A. Hanekamp, V. Y. Reddy, M. R. Kaazempur-Mofrad, and V. Rasche, "Non-rigid registration for fusion of carotid vascular ultrasound and mri volumetric datasets," in *Medical Imaging 2006: Image Processing*, J. M. Reinhardt and J. P. W. Pluim, Eds., vol. 6144, no. 1. San Diego, CA, USA: SPIE, 2006, p. 61442E. [Online]. Available: http://link.aip.org/link/?PSI/6144/61442E/1

[10] J. F. Krucker, G. L. LeCarpentier, J. B. Fowlkes, and P. L. Carson, "Rapid elastic image registration for 3-d ultrasound," *IEEE Trans. Med. Imag.*, vol. 21, no. 11, pp. 1384–1394, Nov. 2002.

[11] J. M. Blackall, G. P. Penney, A. P. King, and D. J. Hawkes, "Alignment of sparse freehand 3-d ultrasound with preoperative images of the liver using models of respiratory motion and deformation," *IEEE Trans. Med. Imag.*, vol. 24, no. 11, pp. 1405–1416, Nov. 2005.

[12] R. Shekhar and V. Zagrodsky, "Mutual information-based rigid and nonrigid registration of ultrasound volumes," *IEEE Trans. Med. Imag.*, vol. 21, no. 1, pp. 9–22, Jan. 2002.

[13] J. P. W. Pluim, J. B. A. Maintz, and M. A. Viergever, "Mutual-information-based registration of medical images: a survey," *IEEE Trans. Med. Imag.*, vol. 22, no. 8, pp. 986–1004, Aug. 2003.

[14] B. M. Dawant, "Non-rigid registration of medical images: purpose and methods, a short survey," in *proc. IEEE International Symposium on Biomedical Imaging*, July 2002, pp. 465–468.

[15] W. H. Press, B. P. Flannery, S. A. Teukolsky, and W. T. Vetterling, *Numerical recipes in C: the art of scientific computing*. New York: Cambridge University Press, 1988.

[16] J. V. Hajnal, D. J. Hawkes, and D. L. G. Hill, *Medical image registration*. Boca Raton: CRC Press, 2001.

[17] M. Ouerfelli, V. Kumar, and W. S. Harwin, "Kinematic modeling of head-neck movements," *IEEE Trans. Syst., Man, Cybern. A*, vol. 29, no. 6, pp. 604–615, Nov. 1999.

[18] F. P. Beer, E. R. Johnston, and J. T. DeWolf, *Mechanics of materials*. Boston: McGraw-Hill Higher Education, 2006.

[19] A. Fenster, S. Dunned, T. K. C. Chan, and D. B. Downey, "Inventors, method and system for constructing and displaying three-dimensional images," United States patent 5,454,371, Oct. 1995.