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Automatic Lumbar Motion Analysis Based on Particle Filtering

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Abstract—Spinal motion is produced by complex coordination of nerves and muscles and is constrained by vertebral structure. The observation and measurement of lumbar motion is of great value for clinical diagnosis and surgical plan of lumbar disorders. Digitalized Video Fluoroscopy (DVF) is the most suitable one to image the spine motion but it is quite time consuming. This paper proposes an automatic lumbar motion analysis system (ALMAS) with particle filtering technology. The automatically vertebral tracking for motion analysis was utilized with a friendly-interface, which provides a window for users to process the acquired DVF sequence and to analyze the tracking results. A set of simulation vertebra image were used to evaluate the performance and accuracy of this system. In simulated sequence, the maximal difference is 1.3 mm in translation and 1° in rotation angle. The error is small in x- and y- translation (fiducial error: 2.4%, repeatability error: 0.5%) and in rotation angle (fiducial error: 1.0%, repeatability error: 0.7%). The ALMAS can still track the sequence contaminated by noise with the density ≤ 0.5 . Besides, the results demonstrate that the data from the auto-tracking algorithm shows a strong correlation with the actual measurement and that the ALMAS is highly repetitive. Results from this study showed that ALMAS based on particle filtering are relatively robust and accurate for automatic lumbar motion analysis.

Keywords- Particle Filter; Lumbar Spine; Vertebral Body

I. INTRODUCTION

Low back pain is one of the most common causes of work loss and chronic disability. It has been reported about 80% people experienced low back pain during their life [1-5]. Although the greater efforts have been done on this problem, we still do not have a thorough understanding on its mechanism and behavior [6, 7].

Biomechanical factors play a very important role in low back pain. Reontogenograph is the only way to see the motion of lumbar spine without traumatic procedure and without any painfulness[8]. However, it is difficult to capture the whole motion with conventional radiographic techniques [9], because the number of radiographs obtained is limited by the radiation exposure thus encountered. The advantage of technique give us

the possibility to investigate more detail of the motion without increasing the risk of exposure. Using the video fluoroscopy [10-16], it is capable of revealing the real-time spinal motion at low radiation exposure. It gives the important insight into what actually happens during dynamic body functions.

However, the information, concerning in realization and application at system level in clinic, is rarely reported. Therefore, we develop a new automatic lumbar motion analysis system (ALMAS) which mainly studies the lumbar vertebrae's movement in model. In the original design of this system, the kinematic analysis is carried out through calculating the kinematic parameters such as the angle of rotation and translation of each vertebra based on the markers' positions on the vertebrae in each frame of the sequence. The manual landmarking procedure is very tedious and laborious. Furthermore, it can be error prone. There have been several previous attempts to automate the landmarking procedure. In this study, we propose the automatic measurement on the lumbar vertebrae motion using the particle tracking algorithm. This paper presents our simulation study to testify the robustness and the reliability of this analysis.

II. PARTICLE FILTER TRACKING ALGORITHM

The particle filter estimates the posterior distribution of the x- and y- displacement (Δx_t , Δy_t) and the change in orientation ($\Delta \theta_t$) from the frame t to $t+1$ which are formulated in a state vector as

$$X_t = [\Delta x_t, \Delta y_t, \Delta \theta_t]^T \quad (1)$$

The particle filter estimates the posterior distribution $p(X_t|Z_{1:t})$ of X_t from a noisy collection of observations (or measurements) $Z_{1:t} = (Z_1, Z_2, \dots, Z_t)$ from each frame of the fluoroscopy sequence arriving in a sequential fashion. From the frame $t-1$ to t , the particle filter generates N samples (called particles) according to the prior distribution of a state transition model $p(X_t|X_{t-1})$ for each vertebra to predict the location and orientation in frame t . The observation model measures the goodness of fit between the projected spline contour (according to the particles) and the vertebra edge. This forms the likelihood distribution $p(Z_t|X_t)$ of the measurements. The best particle is the one having the best match. The particles are then

resampled and the state estimate \hat{X}_t is approximated from the posterior distribution $p(X_t|Z_{1:t})$ by a set of particles $(X_t^{(n)}, \omega_t^{(n)})_{n=1}^N$ weight with $w_t^{(n)}$ and $\sum_{n=1}^N w_t^{(n)} = 1$. By applying Sequential Importance Resampling (SIR) to each time step to prevent the degeneracy problem, the weight for each particle n becomes

$$\omega_t^{(n)} \propto p(Z_t | X_t^{(n)}) \quad (2)$$

$$p(X_t | Z_{1:t}) \approx \sum_{n=1}^N \omega_t^{(n)} \delta(X_t - X_t^{(n)}) \quad (3)$$

where $\delta(\cdot)$ is a Dirac delta function. The kinematic parameters in the state vector \hat{X}_t at frame t are computed by using the minimum mean square error (MMSE) estimate.

$$\hat{X}_t \approx \frac{1}{N} \sum_{n=1}^N \omega_t^{(n)} X_t^{(n)} \quad (4)$$

The control vector for the frame t, C_t , is obtained from the one at t-1, C_{t-1} , and \hat{X}_t after which C_t and \hat{X}_t are passed back to the particle filter for the next iteration.

III. PERFORMANCE ASSESSMENT WITH SIMULATED SEQUENCE

A. Collection of sequence

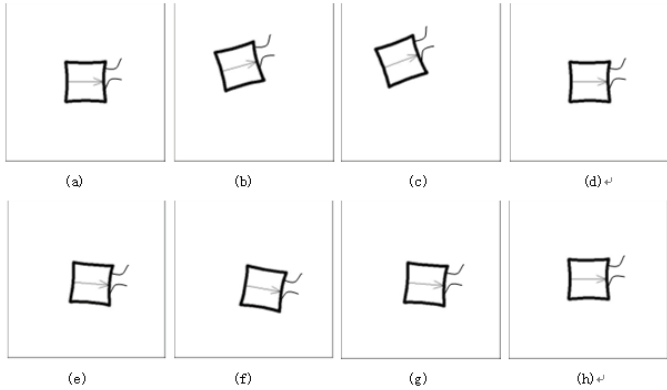


Figure 1. Simulation vertebra set.

(a) $x = 0, y = 0, \theta = 0^\circ$. (b) $x = -10, y = -10, \theta = 10^\circ$. (c) $x = -20, y = -20, \theta = 20^\circ$. (d) $x = 0, y = 0, \theta = 0^\circ$. (e) $x = 5, y = 5, \theta = -5^\circ$. (f) $x = 10, y = 10, \theta = -10^\circ$. (g) $x = 5, y = 5, \theta = -5^\circ$. (h) $x = 0, y = 0, \theta = 0^\circ$.

The simulated sequence consists of 61 frames of a drawn vertebra in motion (Fig 1). The vertebra moves by 1mm in x- and y- translation and 1° in rotation angle in each frame of the simulated sequence. For testing the robust of the VATS to noise, a new sequence is produced by adding the noise, such as “salt & pepper” to degrade the image quality (Fig 2). Furthermore, the histogram equalization and filter are not applied to the specific sequence. The intensity values of the

sequence are scaled to $[0 \ 1]$ such that both the image and noise are of the same scale.

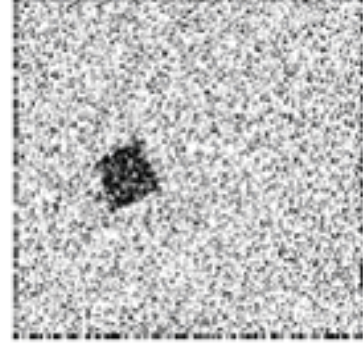


Figure 2. Example of contaminated image (frame 14 in figure 1) with Gaussian noise ($\mu = 0, \sigma^2 = 0.35$)

B. Parameters setting

The vertebra starts at the beginning as the arrow shown in Fig. 1. The angle between the arrow straight and horizontal direction is defined as 0° in the first frame Fig. 1 (a). The centroid of the drawn vertebral is the coordinate origin. The vertebra will come back to the initial position in one cycle movement. The range of motion is preset respectively at $-20 \sim 10$ (mm), $20 \sim -10$ (mm) in x- and y- translation and $20^\circ \sim -10^\circ$ in rotation angle by 1 mm and 1° between the adjacent frames.

Each sequence is initialized by placing about 50 control points along the vertebra’s edge on the first frame. Each vertebra used 2000 particles, and $[\Delta X_t^2, \Delta y_t^2, \Delta \theta_t^2]$ was set as $[4, 1, 0.5]$.

C. Results

Fig. 3 illustrates the trajectories of vertebra in the simulated sequence. The Simulated results (solid line) are the average value of 6 trails by placing the control points 6 times. The true value (dotted line) is preset according to IV B. Parameters setting. In the 6 trials, the fiducial error is 2.2% (0.2%) in x-translation, 2.2% (0.2%) in y-translation, and 4.2% (0.9%) in rotation angle. For examining the magnitude of error, we preset five points in the simulated sequence. The worst error is 0.4° in rotation angle.

In the sequence added the “salt & pepper” (density = 0.50), the tracking results is well. However, the outcome is not good when the density > 0.50 . The image contaminated by “salt & pepper” is seen in Fig. 2. The tracking results of the contaminated sequence are illustrated in Fig. 3 in dashed line. In Fig. 3 (b), the positive direction of the y-axis goes down vertically because the origin of the coordinate was set in the upper left corner.

IV. DISCUSSION

The ALMAS is developed in a medical system in a clinical application. It is able to track the vertebrae of the lumbar spine and to estimate the dynamic motion of the spine in most cases. The development of auto-tracking technology was mainly attributed to the application of DVF and the improvement of tracking algorithm [17]. The ALMAS overcomes those faults. With its application in clinic it is possible to standardize the spine motion and quantify the pattern of spinal movement.

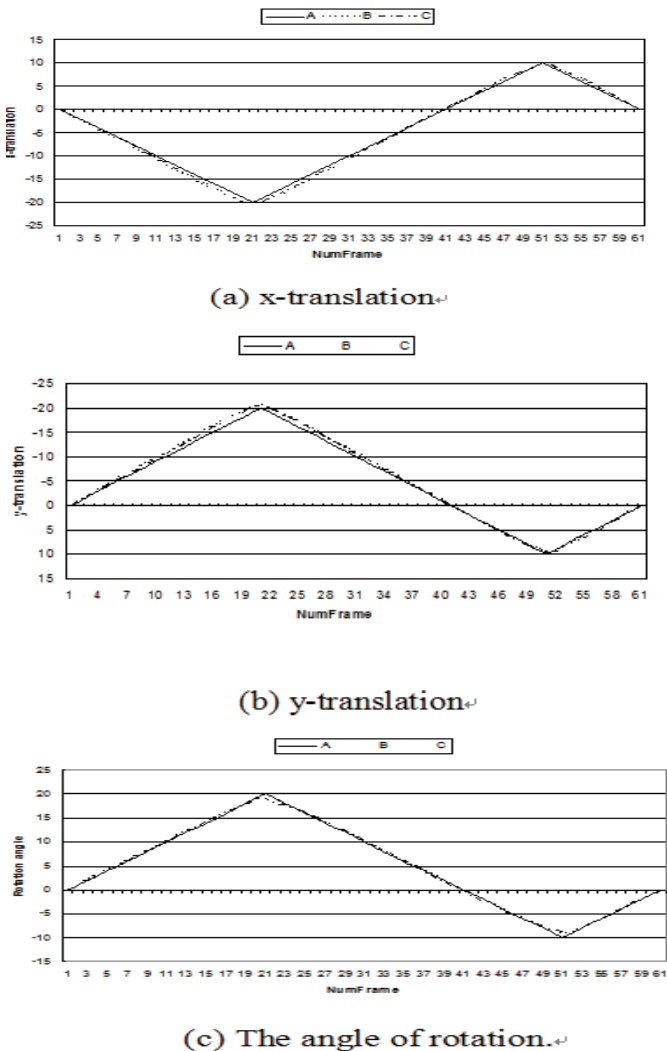


Figure 3. The trajectories of vertebra in simulated sequence. A (solid line) is the true value according to 4.2 Parameters setting. B (dotted line) are the average value of 6 trails by placing the control points 6 times on the first frame of simulated sequence. C (dashed line) is the result of simulated sequence contaminated by "salt & pepper" (density = 0.50).

In the present study, to begin with, the initialization and the number of the control points play an important role in the successful tracking and the accuracy of the tracking results. The accurate location of control points along the vertebra's edges is the key to improving accuracy. Furthermore, the parameter setting is also important. We can get the best results only when the samples and variance are reasonably set. The automatic tracking results are very close to the actual

measurement or the preset value. The translation and angle are accurate in a certain range. Finally, we can acquire other kinematic parameters such as the intervertebral angle and translation to show a more comprehensive survey.

V. CONCLUSION

The proposed ALMAS provided a new medical system to diagnose the lumbar disorder. It also realized the robustness and reliability in tracking the motions from DVF sequence. The simulation study focuses mainly on the reliability and robustness of the automatic lumbar motion analysis system for the lumbar spine motion. In the simulated sequence, the maximal difference is 1.3 mm in translation and 1° in rotation angle. The repeatability error is 0.5%, 0.5%, 0.7% respectively in x- and y-translation and rotation angle. When the simulated sequence is contaminated by noise with different density, the ALMAS can still track the target motion, which demonstrates that it is robust when density below 0.5. It presents a good reliability and robustness, which make the proposed system have a potential value in the evaluation of spinal medical application.

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