Assessment of Cervical Disk Prosthesis by Means of Video-Fluoroscopy Image Processing

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***Abstract* - Many cervical spine pathologies involve degeneration of the stabilizing mechanisms of vertebrae segments and often cause pain. Abnormal intervertebral motion is an indication for surgery. Currently, spinal fusion surgery is widely adopted to fix the instable vertebral segments but recently, disk arthroplasty is more and more adopted as an alternative to restore normal kinematics and biomechanics of the sick segment and to reduce development of symptomatic adjacent-level degeneration. This study aims to measure intervertebral kinematics by means of image processing of X-ray fluoroscopy videos, which are able to screen patient's neck spontaneous movements of flexion-extension. Vertebrae trajectories are estimated by using image template matching techniques. Then, continuous-time intervertebral kinematics is computed by using spline interpolation. The results, obtained by using real fluoroscopy videos, reveal the possibility of obtaining in vivo information about the continuous evolution of motion of the implanted prosthesis and adjacent segments.**

Keywords - X-ray fluoroscopy, image processing, intervertebral kinematics, disk arthroplasty assessment.

I. INTRODUCTION

Many cervical spine pathologies (e.g. segmental degeneration [1], arthritis [2, 3], chronic whiplash dysfunction [4], etc.) deteriorate tissue, degrade the stabilizing mechanisms of vertebrae segments and often cause pain. Detection of spinal instability (degenerative or traumatic) is based on accurate measurement of intervertebral kinematics [5]. In particular, forward displacement of the vertebrae greater than 3.5mm and angle between adjacent endplates greater than 11 degree is regarded as a sign of instability [6] and indication for surgery. Currently, anterior cervical diskectomy with interbody fusion and plating is the predominant technique used in the treatment of segmental instability, symptomatic disk herniation, spondylosis, etc [7]. Spinal fusion drastically limits the range of motion of the segment. Recently, disk arthroplasty, which provides increased stability without limiting so much the range of motion, is more and more adopted in contrast to vertebral fusion procedures. The principal aim of disk arthroplasty is to restore the normal kinematics and biomechanics of the spinal segment affected (motion-preservation strategy). Advantage of arthroplasty over standard arthrodesis techniques should be the reduction in the development of symptomatic adjacent-level degeneration. Following decompression of the neural elements, disk arthroplasty allows restoration of disk height and maintenance of spinal alignment.

However, it is very difficult to measure the intervertebral kinematics in vivo, both for healthy segments and for implanted prostheses. Indeed, direct measurement of the intervertebral kinematic implies invasive and complex techniques and are not suitable for diagnosis. In addition the physiological, little range of motion of a vertebral segment requires accurate measurements. Current measurements are currently achieved in clinical environment by means of functional flexion-extension radiographies [8-10]. This method takes into account only few, end-of-range spinal positions, without considering the whole motion; moreover, the manual selection required on radiographies causes relatively large inaccuracies. Other, non-radiographic methods are unable to accurately measure segmental motion [11-14]. An emerging technology based on computerized video fluoroscopy analysis is being proposed as an alternative capable of providing quantitative and accurate results about segmental motion in vivo [15-21]. These measurements of intervertebral kinematics may also help in evaluating cervical arthroplasty, assessment of disc prosthesis performance, post-surgery follow-up, rehabilitation, etc. [22–24].

This study proposes a methodology to measure the cervical intervertebral kinematics to assess disk prosthesis and adjacent segments motion. Videofluoroscopy images processing allows objective in-vivo measurements and a continuous description of spontaneous patient motion (not limited to end range positions) during flexion extension of the neck.

II. MATERIALS AND METHODS

A. Fluoroscopy image acquisition

Patient's spontaneous motion was screened by means of a digital fluoroscope Stenoscop, by GE Medical Systems. Patients sat in a comfortable chair and were tied to the back with adjustable, fabric belts to ensure shoulder immobilization. The image intensifier was placed as close as

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possible to patient's neck to ensure visibility of the cervical spine during the whole motion. Patients were invited to perform their maximal spontaneous flexion- extension movement of the neck in the sagittal plane with a constant, smooth and limited velocity. Patients familiarized with the environment and repeated the assigned movement many times before recording, under the supervision of the physicians to ensure proper performances. Whole flexion- extension motion takes about 30 seconds. X-ray tube was set to 1 mAs and 50 kVp; digital images were acquired at 4 frame/sec; images are 576 by 576 pixels wide; pixel size is 0.45 by 0.45 mm; image intensity has 8-bit precision. Geometrical distortions were tested by means of a calibration phantom. Fig. 1 shows an image of the neck of patient # 2. The metallic part of the disk prosthesis is clearly visible at level C5-C6, the anchoring rods of the implants, inserted into the vertebral bodies, are also evident.

Fig. 1. Example of a videofluoroscopy frame of patient # 2, who carry a disk prosthesis at level C5-C6 (note the metallic part of the prosthesis)

B. Image processing

The number of X-ray photons necessary for the formation of a fluoroscopic image is much less than that used in conventional radiology. This drastically reduces the radiation dose delivered to patient but causes a large amount of quantum noise [25]. Quantum noise retains Poisson's statistical distribution and its strength depends on local image luminance [26]. Measurements of actual image noise were achieved by means of an accurate fluoroscopy noise model [27]. First, the relationship between pixel luminance and noise variance was estimated. Then, fluoroscopy images were pre-processed by means of a specific filter [28], which performs conditioned average operations adapted to the local noise level. The filter operates both in space and time and it is able to preserve edges, even for moving objects: actually, noise suppression is exclusively performed by averaging the neighborhood (in space and time) data that are likely included in the local noise statistic. Cervical vertebra tracking throughout the video was obtained by means of image template matching [29, 30], exclusively in the sagittal plane [15, 16, 20]. Vertebra is considered as a rigid body and a specific template was assigned to each vertebra. The template includes those parts of the vertebral projection edges that do not overlap along the motion, neither with adjacent vertebrae nor with mobile part of the disk prosthesis. In general, vertebra templates included the anterior part of the body and the spinolaminar junction of the spinous process, while facet joints and prosthesis were excluded. Vertebra registration is based on matching of bones edges and template match is operated using the first derivative of the images. Vertebra tracking throughout the video was achieved by matching the opportunely displaced and rotated template on each fluoroscopic frame [31, 32]. Template matching is based on the Gradient, Normalized Cross Correlation (GNCC) similarity index that take into account the horizontal and vertical image gradients.

The formula of GNCC index is:

$$GNCC = \frac{1}{2} NCC\left(\frac{\partial I}{\partial x}, \frac{\partial T}{\partial x}\right) + \frac{1}{2} NCC\left(\frac{\partial I}{\partial y}, \frac{\partial T}{\partial y}\right) \quad (1)$$

where d/dx and d/dy are the gradient operators along directions x and y respectively; I is the current image and T the vertebra template; NCC is the normalized cross correlation operator and can be expressed by the formula:

$$NCC = \frac{1}{n} \sum_{x,y} \frac{\left(f(x,y) - \langle f \rangle\right) \cdot \left(t(x,y) - \langle t \rangle\right)}{\sigma_f \cdot \sigma_t} \quad (2)$$

where n is the number of pixels; t(x,y) the template; f(x,y) a sub image (same template size); <f> and <t> the averages of f and t; σ_f and σ_t the standard deviations of f and t.

The absolute maximum of the GNCC correspond to the best template location on the current image; in this way each vertebra is located on the current image and its x- and y-displacements and angles of rotation are estimated. The vertebra trajectory is then obtained considering the sequence of its location along time and its rigid, planar motion over the sagittal plane is completely described.

C. Intervertebral kinematics estimation

Once obtained all the vertebrae trajectories (relatively to the fluoroscope reference frame), intervertebral kinematics can be computed. By definition, segmental motion is described as the movement of the upper vertebra with respect to the lower vertebra (the latter considered motionless). In order to obtain a continuous-time description of intervertebral motion, the discrete-time data (i.e. the vertebral x- and y-translations and the rotation) can be interpolated. Accordingly with previous studies [19, 20], discrete-time data can be advantageously interpolated by using non-fitting splines. Splines have the advantage to use piecewise polynomial functions to interpolate data. Moreover, the non-fitting splines offer the additional low-pass filtering effect and favorably smooth the noisy experimental data. This is particularly effective for the intervertebral trajectories which results particularly noisy for their construction and for the limited excursion of the segmental motion. The experimental data can be regarded as the superposition of the true signal (intervertebral motion) and the noise due to measurement errors. The actual intervertebral movements can only be smooth and regular (i.e. band-limited), while the measurement errors can be represented by a random, additive, uncorrelated, Gaussian process (i.e. band-unlimited). Therefore, the low pass filter effect of the smoothing splines enhances the motion signal and suppresses the noise. Another way to describe intervertebral motion is to identify the instantaneous center of rotation (ICR) and the rotation angle [31,32]. ICR coordinates are given by the formula:

$$ICR_X = -\frac{v_Y}{\omega} + r_X \, ; \quad ICR_Y = -\frac{v_X}{\omega} + r_Y \qquad (3)$$

where v_X and v_Y are the components of the upper vertebra velocity (first derivative of the displacements); ω is the angular velocity; r_X and r_Y are offset displacements.

It is apparent by the equation (3) that if the angular velocity ω is zero the ICR coordinates go to infinity, which is consistent with the theoretical definition. Therefore, for practical reasons, the ICR was only computed when the angular velocity exceeded a certain threshold value.

III. RESULTS

Fig. 2 shows the cumulative angle of the cervical tract C3-C7 versus time during spontaneous flexion of patient #2, as example; the contribution of each segment is shown too. The prosthesis was implanted at disk level C5-C6.

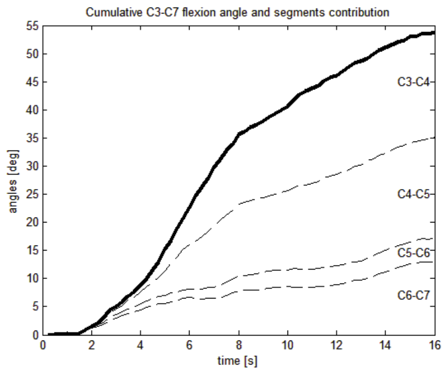

Fig. 2. Experimental, cumulative angle of the cervical spine tract C3-C7 in bold, continuous line during spontaneous flexion; the contribution of each segments is depicted as dashed line.

Fig. 3 and 4 show the intervertebral kinematics of segment C5-C6 (prosthesis). Dots represents experimental data.

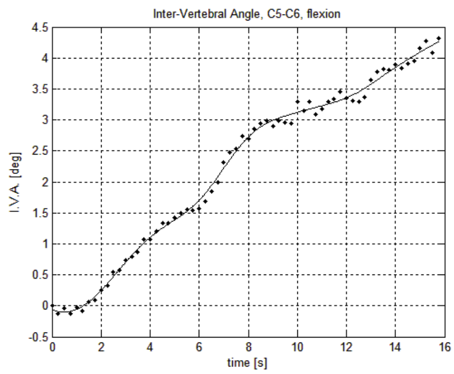

Fig. 3. C5-C6 InterVertebral Angles (IVA). Dots represent discrete-time data while continuous line shows spline interpolation (5th degree polynomials).

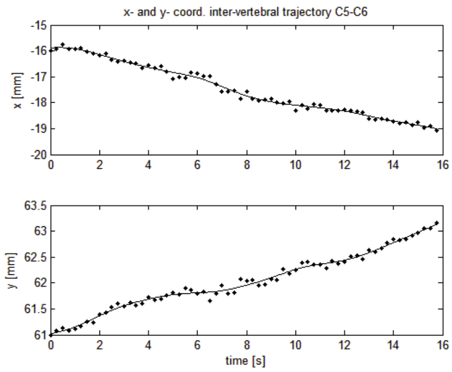

Fig. 4. C5-C6 intervertebral displacements. Dots represent discrete-time data while continuous line shows spline interpolation (5th degree polynomials).

Polynomial spline interpolation allows easy estimation of the vertebra angular and linear velocities (see equation 3). The RMS values of the fitting errors (residual of the interpolation) result 0.08 degree for the intervertebral angle and 0.09 mm and 0.06 mm for the intervertebral x- and y- displacements respectively. Fig. 5 shows the ICR trajectory for the C5-C6 segment superimposed on a fluoroscopy image. Note that the ICRs nearly coincide with the anchoring rods inserted in the C6 vertebral body: the prosthesis rotate around this pivot point, as expected.

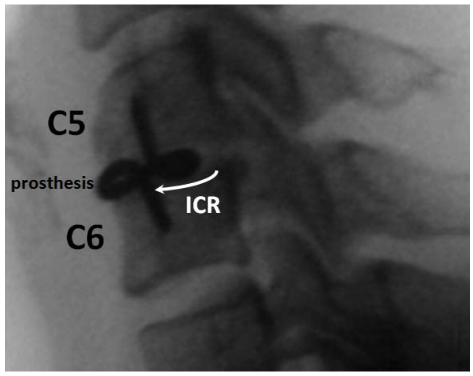

Fig. 5. Fluoroscopy image enlargement C5-C6 segment; the trajectory of the ICR during flexion is shown in white.

IV. COMMENTS AND CONCLUSIONS

Fluoroscopy offers a viable method to non-invasively measure intervertebral kinematics in vivo. Continuous-time motion can be obtained by fluoroscopy video processing. In particular, this study show the possibility to use vertebrae tracking algorithms to measure segmental motion also in presence of a disk prosthesis. This methodology offers a better alternative with respect to the functional radiographies, which take into account only end-of-range spinal positions and require manual landmark selection. Furthermore, this methodology allows reliable estimation of ICR for a spine segment, while other methods only estimate the finite centre of rotation, which is only an approximation. The ICR resulted much more sensible to mild degeneration of disk and ligament [33,34] and, potentially, is a good estimator of segmental instability. Measurements of intervertebral kinematics are an objective diagnostic tool to assess functionality of disk prosthesis and to evaluate alteration of motion of the adjacent cervical segments.

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