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Automatic Vertebral Morphometry Assessment

Sergio Casciaro and Laurent Massoptier

***Abstract* — Diagnosis of vertebral deformation and fracture is a key issue in the management of osteoporosis. Vertebral morphometry is the key solution to assess these vertebral deformities, but it is a tedious operation for the rheumatologist. In this paper, we propose an automatic approach to localize vertebrae and determine the vertebral morphometry. Based on a local phase symmetry measure, our approach shows promising results even on poor quality images. This work was tested on 22 scans of conventional lateral X-rays radiographs and compared to the results obtained by a trained radiologist. It resulted to have acceptable low error rates for localization and vertebral morphometry measures, but with a lack of robustness among images. Amelioration is necessary for images with an unoptimized patient positioning, when the X-ray beam is not perpendicular to the spine.**

***Keywords* — automatic segmentation; vertebral fracture; morphometry; osteoporosis; X-ray images.**

I. Introduction

OSTEOPOROSIS has been defined by the last NIH Consensus Conference [1] as a skeletal pathology characterized by a compromised bone resistance that predisposes a subject to an increased risk of fracture. It is a silent and insidious illness, generally badly known and underestimated by patients and doctors. Favored in its nature by the prolongation of the life, the osteoporosis strongly jeopardizes the life quality of affected people. The acute and chronic pain, the height and mobility reductions, and the deformations of the vertebral column progressively reduce the ability to do the normal daily activities up to the loss, more or less complete, of his/her own self-sufficiency, to finally come to a serious invalidating condition.

Moreover, several studies have demonstrated that the existence of prevalent vertebral fractures confer a high risk of subsequent fractures [2]. Unfortunately, early detection and clinical treatments don't happen in up to two-thirds of vertebral fractures because of difficult evaluations based on common symptoms.

Therefore, vertebral fracture identification is a key issue in osteoporosis management. The bony resistance is a parameter that is evaluated on visual (shape and size), quantitative (bony mass or bone mineral density (BMD) reductions) and qualitative aspects (decreasing of the bony micro-architecture in the osteoporotic subject).

Two assessment methods for vertebral fracture identification are available: the first is the visual assessment and the second is the vertebral morphometry [3]. The former method is the conventional one and is a qualitative reading of a lateral radiograph by a trained radiologist. The latter is based on measurements of anterior (Ha), middle (Hm), and posterior (Hp) heights of vertebral bodies requiring less special skills. The main advantage of conventional radiographs is the high resolution of images. However, the disadvantages of this technique are related to consistent patient positioning, image magnification and distortion, and high radiation dose [4]. Consequently, dual-energy X-ray absorptiometry (DXA) has become the gold standard for BMD measurement, and the *Genant* semi-quantitative method is in use in most clinical trials. Actually the use of purely morphometric criteria is still controversial due to the significant number of false positive generated by this technique [3]-[5].

An automatic algorithm to determine the three vertebral heights (Ha, Hm and Hp) is of significant importance, because manual measurement relies on subjective judgment producing results inaccurately repeatable. Up to these days, in literature, it seems that only algorithms for automatic vertebrae contour detections have been reported, this being the first step to measure Ha, Hm and Hp. Due to the considerable variation in vertebral appearance, it seemed that most researchers had used some form of shape constraints. On one hand, some semi-automatic methods for vertebral segmentation using active contours and active shape modeling techniques have been published [6]-[7]. A recent paper was also published on segmentation of vertebrae on DXA images using Active Appearance Models [8]. Otherwise, vertebrae contours are detected by the polar signature after identification of each vertebra [9]. On the other hand, fully automated segmentation methods are generally based on one of the two following approaches. The first procedure consists on determining the vertebrae contours on the basis of landmark points [10]. The second procedure is a template-matching based method using customized Hough transform [11] or mathematical morphology [12]. However, de Bruijne et al developed a fully automatic method for segmenting vertebrae of radiographs using shape filtering particle [13], and another high performance solution to the problem of vertebra segmentation in X-ray images is a hierarchical approach combining three different techniques (Hough transform,

Sergio Casciaro is with the Division of Biomedical Engineering Science and Technology, Institute of Clinical Physiology, Lecce, Italy (e-mail: casciaro@ifc.cnr.it)

Laurent Massoptier is with the Division of Biomedical Engineering Science and Technology, Institute of Clinical Physiology, Lecce, Italy (corresponding author to provide phone: (+39) 0832-422-311; fax: (+39) 0832-422-340; e-mail: massoptier@ifc.cnr.it)

active shape models, and deformable models) [14].

This paper intends to bridge the gap between vertebral segmentation and vertebral morphometry. Firstly, the vertebrae contours are detected and secondly, characteristical vertebra heights are measured. All this work is automatically performed as presented in section II. In section III first experimental results will be showed and discussed. Finally section IV will conclude this paper and will give possible future directions.

II. Methodology

To achieve fully automatic vertebral morphometry on lateral X-ray images, a localization of the vertebrae was necessary, meaning in our approach the position of the six reference points (P1, P2, M1, M2, A1 and A2) showed in Fig.1.

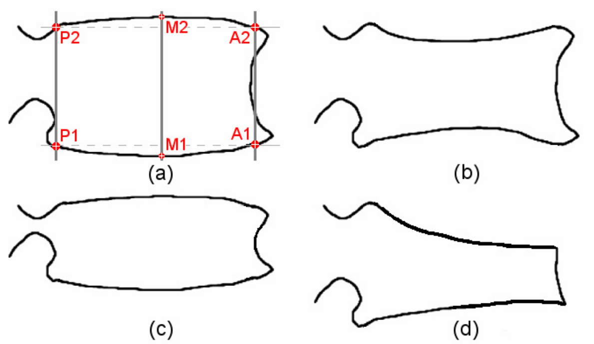

Fig. 1. Conventional profile of a vertebra with the 6 points used for the vertebral morphometry (a), biconcave deformity (b), crushing deformity (c), and wedge deformity profile (d).

A. Vertebral morphometry

The vertebral morphometry is a standard method to detect vertebral deformities using lateral X-ray images. It is based on the use of the three dimensions of the vertebrae (Ha, Hm and Hp) that are defined as follows:

$$Hp = || P1–P2 ||_2 \,, Ha = || A1–A2 ||_2 \,, \quad (1)$$
$$Hm = || M1–M2 ||_2 \,.$$

with the notation indicated in Fig.1.

Numerous methods have been described in literature to distinguish deformed and non-deformed vertebrae with these measures [15]. In this work, the Melton approach [16] was used and enabled to differentiate three deformities (Fig.1) by calculating six ratios:

-- Biconcave deformity with the ratio Hm/Hp,

-- Wedge deformity with the ratio Ha/Hp,

-- Crushing deformity with the four ratios Hp/Hp(±1) and Ha/Ha(±1), where +1 and -1 stand respectively for the upper and the lower adjacent vertebrae.

Then, a threshold of 85% of the normal reference ratio was used to define vertebral deformity.

B. Vertebrae localization

The challenging problem was to determine accurately and automatically the position of the 6 points representing our vertebra model.

First of all, a local phase-based measure of symmetry was used to emphasize the vertebrae borders. This symmetry measure was significant in that it was a low level operator and a dimensionless measure providing an absolute sense of the degree of local symmetry independently of the image illumination or contrast [17].

Then, as many other researchers in this filed, we used a shape constraints characterization by looking for every shape that could be an inter-vertebral disc using a recognition function. This function gave to each pixel a probability to have an inter-vertebral disc centered on this pixel. Indeed, the novelty of this approach was to constraint the detection with the shape of an inter-vertebral disc (thin rectangular shape with two bright borders) that was much more characteristic than the vertebra itself (square shape with four borders). Maximal recognition responses were selected and considered as the center of an inter-vertebral disc.

Finally, the inter-vertebral borders were refined using the local phase symmetry measure. These borders were assigned two by two using a distance criterion in order to form a vertebra. Then, the 4 corners of the vertebra – P1, P2, A1, and A2 – were localized on these borders by maximizing the area formed by this quadrilateral. To complete our vertebral model, M1 and M2 were positioned at equal distance from P1 and A1 and from P2 and A2, respectively.

III. Experimental Results

We have tested and quantified the performance of our method in three separate experiments following our main algorithmic steps. Twenty-two (22) conventional lateral radiographs were collected without asking for neither specific acquisition parameter settings nor patient clinical situation and identification data in the full respect of the national privacy laws. This was done in order to face the variability of radiology centers. Images were of various sizes going from one-half to one-eighth of a classical radiographic sheet, depending on the format in use in the radiology center where patient went. All radiographs were first scanned and saved as TIFF file without compression.

Our three experiments were based on the comparison between the results coming from our automatic approach and the ones obtained by a trained radiologist. First we calculated the detected inter-vertebral discs as a percentage of the real number. Then, we measured the localization error of the 6 points from our vertebra model referring to the manual positioning. The final experiment concerned the vertebral morphometry and its percentage of error, always considering the manual estimation as the gold standard.

A. Experiment 1: inter-vertebral disc detection

The detection of inter-vertebral discs was really important because the next step of our algorithm was based on this first result. Among the 22 patients' radiographs, 128 inter-vertebral discs were counted with some disparities between images (from 3 to 9 discs on each image). It represented also 106 vertebrae integrally present on images.

In some cases, our automatic approach found all the inter-vertebral discs, while for some other images it missed up to two discs. In total, 110 inter-vertebral discs were well detected representing a percentage of success equaling 85.94%. Therefore, 88 vertebrae were detected giving a percentage of success equaling 83.02%.

Two explanations of misdetection were revealed by the analysis of the images. Some of the misdetected inter-vertebral discs were at a border of an image, i.e. part of the discs was outside the image field of view. Then, the similarity score was to low to identify an inter-vertebral disc. The other misdetections were located in very low contrast zone. Even if the local phase symmetry measure was independent of the contrast, some features considered to be of little significance could be marked as having strong symmetry. Then, in some low contrast areas, the symmetry measure of the discs were too low compared to other untargeted features in order to be detected without other false alarms. Upon this consideration the success score could be increased after a better definition of inter-vertebral discs in the radiography.

Then, this percentage of success is good because our method works also in low contrast situations (Fig.2a).

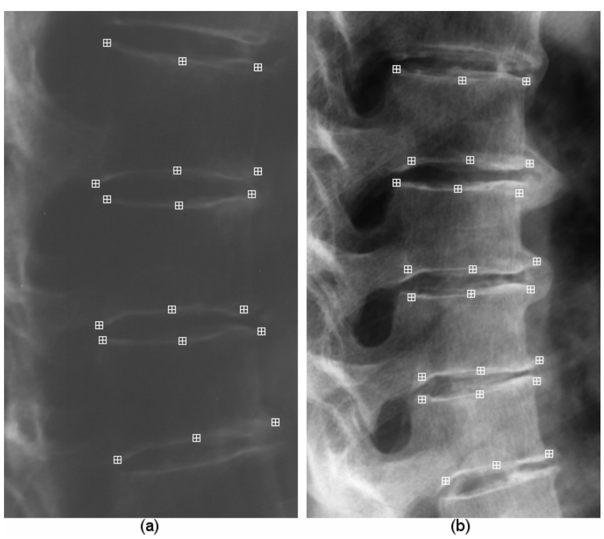

Fig. 2. Vertebrae localization. Examples on a low contrast X-ray image (a), and a good quality X-ray image (b). In white are the positions of the 6 characteristical points found by the automatic approach.

B. Experiment 2: position of vertebrae

The second experiment dealt with the position accuracy of the 6 points defining our vertebra model for all 88 detected vertebrae. The position found by our algorithm was compared to the one placed by the radiologist. The distance between these two points was normalized by the length of the vertebra. This length was supposed to be relatively invariant from one patient to another. Indeed, it was the unique solution to compare the results between vertebrae, because the images resolution was unknown. Therefore, the error was calculated by the following formula:

$$error(Zi) = \frac{\left\| Zi_{auto} - Zi_{hand} \right\|_2}{\left\| P1_{hand} - A1_{hand} \right\|_2} \quad (2)$$

The mean and the standard deviation of errors were reported in percentage in Table I for the 6 points localizations. It shows that the performances of our algorithm were independent on the points' category, because the mean localization errors for all the 6 points had the same order of magnitude, around 5 and 8%, that can be considered as relatively low. However, the standard deviation was too high, because it almost equaled its corresponding mean value.

TABLE I
VERTEBRAE LOCALIZATION ERROR

	P1	P2	M1	M2	A1	A2
m	8.01	5.93	6.06	5.00	7.21	8.22
sd	6.78	5.80	5.19	4.51	6.50	7.74

m stands for mean, sd stands for standard deviation.
The values are expressed in percentage.

This phase of our approach was certainly the most challenging part of our work. Indeed, even a trained radiologist encountered difficulties to place some vertebral characteristical points. Low contrast zone was a part of the difficulties, but it was mainly tackled by the symmetry measure. The main difficulty came from the imaging itself: vertebrae are generally not aligned with the X-ray beam. Vertebral borders were not superimpose and enlarged the impression of their size. So, there was a relative uncertainty for the manual positioning, but the same problem was found for the automatic case.

This phenomenon gave also a low local phase symmetry measure generally in the middle of the vertebral borders. That produced a discontinuity on the segmented borders. One of the two parts was rejected by our algorithm, so the segmented vertebra was drastically cut of a third of its real size.

C. Experiment 3: morphometry measure

The third experiment analyzed the ultimate goal of our work: the vertebral morphometry. The six ratios of the Melton approach were calculated for both automatic and manual methods and for all 88 detected vertebrae. Then, the relative error between both methods were determined as follows,

$$error(R) = \frac{| R_{auto} - R_{hand} |}{R_{hand}} \quad (3)$$

where R represents one of the six ratios.

Table II was a descriptive synthesis of the vertebral morphometry measures found by our automatic approach and by the radiologist. Both methods showed that wedge and biconcave deformities were the most numerous among our 22 patients. Mean and standard deviation values were relatively the same for all ratios and both methods, leaving a chance to have a common medical diagnosis to both methods.

TABLE II
VERTEBRAL MORPHOMETRY FOR AUTOMATIC AND MANUAL MEASURES

	wedge	bi-concave	crush post -1	crush post +1	crush ant -1	crush ant +1
m A	0.88	0.89	1.00	1.01	1.00	1.02
sd A	0.10	0.07	0.10	0.10	0.14	0.14
m M	0.89	0.84	0.99	1.02	0.99	1.02
sd M	0.06	0.05	0.08	0.08	0.08	0.08

m and sd stand respectively for mean and standard deviation, while A and M stand respectively for automatic and manual measures.

But Table III clarified this point. Note that we used the Melton approach meaning that a threshold of 85% of the normal reference ratio was used to define vertebral deformity. This 85% threshold implied that a maximum error of 15% (the normal reference ratio is smaller than 1) was acceptable because it should not change the medical diagnosis. The results on Table III showed a mean error of 7% with a standard deviation around 6-7%. Therefore, a confidence interval of about 60% was given. After applying the 85% threshold on the data, we verified that our automatic method gave 64% agreement on deformities. Furthermore, we obtained a perfect sensitivity of 100% because no false negative was given, and a specificity of 42.8%. This specificity rate was clearly too low and was the direct consequence of wrong vertebral localizations.

TABLE III
VERTEBRAL MORPHOMETRY ERROR

	wedge	bi-concave	crush post -1	crush post +1	crush ant -1	crush ant +1
m	7.17	7.09	7.14	6.93	7.76	7.57
sd	5.81	6.60	6.86	6.26	7.82	6.96

m stands for mean, sd stands for standard deviation.
The values are expressed in percentage.

IV. CONCLUSION & FUTURE WORK

This paper investigated the feasibility of the automatic vertebral morphometry and its suitability for subsequent clinical assessment. Even on low contrast images, it gave promising results with an error rate around 7% for both vertebral corners localization and vertebral morphometry measures. However, limited robustness underlined by a too high standard deviation of these error rates must be addressed. Therefore, our automatic approaches gave the same diagnosis than the trained radiologist in 64% of cases. The similarity of the results, between the automatic and the manual morphometric measurements presented in Table II, clearly gives a chance for a further clinical application of this new method, provided that specificity is improved. Indeed, the main encountered difficulty was the low symmetry measure of the middle reference point vanishing up to one-third of morfometry evaluations (paragraph III.B).

So, a future work is to tackle this problem, and a possible way is to connect two detected parts of an incomplete vertebral border by a contour closing technique based on proximity, curvature and symmetry characteristics.

REFERENCES

[1] NIH Consensus Development Panel on Osteoporosis Prevention, Diagnosis, and Therapy, “Osteoporosis prevention, diagnosis, and therapy”, in *Journal of American Medical Association*, vol. 285(6), pp. 785-795, Feb. 2001.

[2] C.M. Klotzbuecher, P.D. Ross, P.B. Landsman, T.A. Abbott, and M. Berger, “Patients with prior fractures have an increased risk of future fractures: a summary of the literature and statistical analysis”, in *J Bone Miner Res*, vol. 15, pp. 721–739, Apr. 2000.

[3] L. Ferrar, G. Jiang, J. Adams, and R. Eastell, “Identification of vertebral fractures: an update”, in *Osteoporosis Int*, vol. 16(7), pp. 717–728, Jul 2005.

[4] L. Pavlov, G.D. Gamble, and I.R. Reid, “Comparison of dual-energy X-ray absorptiometry and conventional radiography for the detection of vertebral fractures”, in *Journal of Clinical Densitometry*, vol. 8(4), pp. 379-385, 2005.

[5] D.M. Black, L. Palermo, M.C. Nevitt, H.K. Genant, R. Epstein, R. San Valentin, S.R. Cummings, “Comparison of methods for defining prevalent vertebral deformities: the Study of osteoporotic fractures”, in *J Bone Miner Res*, vol. 10(6), pp. 890–902, Jun 1995.

[6] S. Lobregt and M.A. Viergever, ”A discrete dynamic contour model”, in *IEEE Transactions on Medical Imaging*, vol. 14(1), pp. 12–24, Mar. 1995.

[7] P.P. Smyth, C.J. Taylor, and J.E. Adams, “Vertebral shape: automatic measurements with active shape models”, in *Radiology*, vol. 211(2), pp. 571–578, May 1999.

[8] M. Roberts, T. Cootes, and J. Adams. Vertebral morphometry: semiautomatic determination of detailed shape from dual-energy X-ray absorptiometry images using active appearance models, in *Invest Radiol*, vol. 41(12), pp. 849-859, 2006.

[9] M. Benjelloun, H. Tellez, and S. Mahmoudi, “Vertebra edge detection using polar signature”, in *18th Int Conf Pattern Recognition*, vol. 1, pp. 476–479, Aug. 2006.

[10] L.R. Long, and G.R. Thoma, “Landmarking and feature localization in spine X-rays”, in *J Electron Imaging*, vol. 10, pp.939–956, Oct. 2001.

[11] Y. Zeng, M.S. Nixon, and R. Allen, “Automated segmentation of lumbar vertebrae in digital videofluoroscopic images”, in *IEEE Transactions on Medical Imaging*, vol. 23(1), pp. 45–52, Jan. 2004.

[12] V.P. Kumar, and T. Thomas, “Automatic estimation of orientation and position of spine in digitized X-rays using mathematical morphology”, in *Journal of Digital Imaging*, vol. 18(3), pp. 234–241, Sep. 2005.

[13] M. de Bruijne, and M. Nielsen, “Image segmentation by shape particle filtering”, in *Proc. International Conference on Pattern Recognition*, vol. 3, pp. 722–725, Aug 2004.

[14] G. Zamora, H. Sari-Sarraf, and R. Long, “Hierarchical segmentation of vertebrae from X-ray images”, in *Proceedings of the SPIE Medical Imaging*, vol. 5032, pp. 631–642, May 2003.

[15] F. Duboeuf, D.C. Bauer, R.D. Chapurlat, J.M. Dinten, and P. Delmas, “Assessment of vertebral fracture using densitometric morphometry”, in *Journal of Clinical Densitometry*, vol. 8(3), pp. 362–368, 2005.

[16] L.J. Melton, S.H. Kan, M.A. Frye, H.W. Wahner, W.M. O’Fallon, and B.L. Riggs, “Epidemiology of vertebral fractures in women”, in *Am J Epidemiol*, vol. 129(5), pp.1000–1011, May 1989.

[17] P. Kovesi, “Symmetry and asymmetry from local phase”, in *Proc. 10th Australian Joint Conference on Artificial Intelligence*, vol. 1, pp. 185–190, Dec. 1997.