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A NOVEL FULLY AUTOMATIC ALGORITHM FOR ACCURATE VERTEBRAL MORPHOMETRY

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Abstract: Vertebral morphometry is a common clinically-used method for vertebral fracture detection and classification, based on height measurements of vertebral bodies in radiographic images. This method is quantitative and does not require specific operator skills, but its actual accuracy is affected by errors made during the time-consuming manual or semi-automatic measurements. In this paper, we propose an innovative fully automatic approach to vertebral morphometry. A novel algorithm, based on a local phase symmetry measure and an "Active Shape Model", was implemented and tested on lateral X-ray radiographs of 50 patients. Thoracic and lumbar vertebral bodies in each image were independently segmented and measured by both the automatic algorithm and an experienced radiologist, whose manually-obtained results were assumed as the ground truth. The algorithm showed reasonably low error rates regarding both vertebral localization and morphometric measurements with a sensitivity of 86.5% and a perfect specificity of 100%, because no false positive were present. Furthermore, its performance did not appreciably worsen on poor quality images, emphasizing a significant potential for a prompt translation into clinical routine.

Keywords: automatic segmentation; vertebral fracture; morphometry; osteoporosis; active shape model.

1. INTRODUCTION

Osteoporosis is defined as a systemic skeletal disease characterized by a decrease in bone mass and density that can lead to a compromised bone resistance [1], predisposing a subject to an increased risk of fracture. In particular, it has been demonstrated that vertebral fractures are the most common of all osteoporotic fractures [2] and are associated with an increased mortality rate, loss of independence in elderly patients, and impaired quality of life [3]. For these reasons the early and accurate identification of patients with vertebral fractures is crucial in order to properly stratify fracture risk and choose the best suited prevention strategies [3]. Unfortunately, up to two-thirds of vertebral fractures do not come to clinical attention because patients and physicians are not aware of the common symptoms [4]. In fact, the majority of osteoporotic vertebral fractures actually consist in mild vertebral deformities (with a reduction in height within 20–25%), which are often asymptomatic and occur in absence of a specific trauma [3].

Two assessment methods for vertebral fracture identification are currently available in clinical routine: the visual assessment of a lateral radiograph by a well-trained radiologist and the vertebral morphometry [5,6], which is based on measurements of front (Ha), middle (Hm), and rear (Hp) heights of vertebral bodies. The former method is qualitative and needs an experienced operator, while the latter is quantitative and requires less specific skills. On the other hand, vertebral morphometry represents a tedious and time-consuming operation, whose accuracy is often affected by errors made during manual or semi-automatic measurements.

In this work we present a novel fully automatic algorithm for vertebral body segmentation and morphometric measurement, whose final goal is to reduce errors due to manual and semi-automatic processes. The proposed approach combines literature-reported methods for automatic vertebral segmentation with subsequent morphometric measurements, without requiring any operator action. In general, fully automated methods for vertebra segmentation apply a procedure that consists in determining the contours of vertebrae on the basis of landmark points [7] or mathematical morphology [8]. In X-ray images, the solution to the problem of vertebra segmentation is typically represented by an approach combining different techniques based on Hough transform and deformable contours [9,10].

Our fully automatic method identifies the vertebrae and detects their edges. Subsequently, the algorithm measures the characteristic vertebra heights (Ha, Hm, Hp) [11] and determines vertebral deformities through the Melton approach [12]. All this work is automatically performed by our algorithm, as presented in section 2. In section 3 the experimental results will be showed and discussed. Finally, section 4 will provide the paper conclusions.

2. METHODOLOGY

Vertebral morphometry is a quantitative method to identify osteoporotic vertebral fractures based on the measurement of vertebral heights [13]. Vertebral morphometry may be performed on conventional spinal

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radiographs (MRX: morphometric X-ray radiography) or on images obtained from dual X-ray absorptiometry (DXA) scans (MXA: morphometric X-ray absorptiometry) [2]. This technique is based on the use of three dimensions of the vertebrae (Ha, Hm and Hp) that are defined as follows:

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

Where Hp, Ha and Hm are respectively the rear, the front and the middle height of the vertebra (Fig. 1). Numerous methods have been described in literature to distinguish deformed and non-deformed vertebrae using these measures [11]. In this work, we used the Melton approach [12]. This approach enabled us to differentiate three kinds of possible vertebral deformities by calculating six ratios:

- Biconcave deformity (collapse of the central portion of both vertebral body endplates) if Hm/Hp<0.85.
- Wedge deformity (collapse of the anterior portion of the vertebral body) if Ha/Hp<0.85
- Crushing deformity (collapse of the entire vertebral body, or anterior or posterior vertebral body respect the upper and the lower adjacent vertebrae) if Hp/Hp(±1)<0.85 and/or Ha/Ha(±1)<0.85, where +1 and -1 stand respectively for the upper and the lower adjacent vertebrae.

Therefore, a threshold of 85% of the normal reference ratio was used to define vertebral deformity [12],

The main problem in implementing the fully automatic vertebral morphometry was the accurate determination of the position of each vertebra on the X-ray image and then the correct placement of the six reference points (rear vertebral corners P1, P2; middle vertebral points M1, M2; front vertebral corners A1 and A2) for each detected vertebra (Fig. 1). First, a local phase-based measure of symmetry was used to emphasize the vertebra borders. This symmetry measure was a dimensionless low-level operator that provided an absolute sense of the degree of local symmetry, independently of the image illumination or contrast [14].

Then, we looked for every shape that could be a vertebra using a recognition function. This function gave to each pixel a probability to have a vertebra centered on the pixel itself. Maximal recognition responses were selected and considered as the center of a vertebra [4].

Finally, to find the position of the six points we had to refine the vertebra borders. To determine these borders we used the Active Shape Model (ASM) method [15].

The ASM uses a statistical model of the shape of an object (in our case the vertebra) that is repeatedly deformed by ASM to fit in an example of the structure represented by the model.

In order to build the vertebral model, we used an annotated training set (Fig. 2). The training set was realized through a manual segmentation of a set of training X-ray images of vertebrae, followed by manual landmarking methods to describe the edge of each vertebra.

It is a common practice to choose as landmarks the corners of the vertebra and a reasonable number of equidistant points between the corners [16].

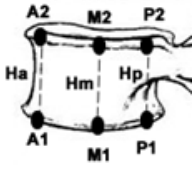

Figure 1. Conventional profile of a vertebra with the 6 points used for vertebral morphometry. Hp, Ha and Hm are respectively the rear, the front and the middle height of the vertebra.

We positioned the center of the model so that it was overlapped to the center of the detected vertebra. The ASM method iteratively deformed the model by correcting the position of each point in the edges, aiming to match the model to the detected vertebra in the radiographic image [15]. The four corners of the vertebra (the rear points P1, P2 and the front points A1, A2) were localized on the borders by maximizing the area formed by the corresponding quadrilateral. To complete our vertebral model, the middle points M1 and M2 were positioned at equal distance from P1 and A1 and from P2 and A2, respectively.

We tested and quantified the performance of our method by analyzing 50 conventional lateral radiographs from 50 different patients. They were collected in the full respect of the national privacy laws. All the collected radiographs were scanned and saved as PNG files.

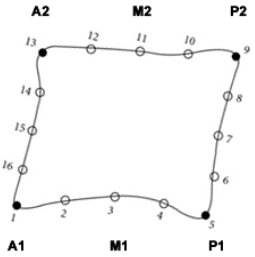

Figure 2. Vertebra model landmarks. Points 1, 5, 9, and 13 identify the corners while the other points are scattered along the edges.

The performance tests were based on the comparison between the results coming from our automatic approach and those obtained from the manual measurements carried out by an experienced radiologist.

First, we measured the localization error of the six points between our vertebra model and the manual positioning as the geometric distance between the point automatically fixed by the automatic algorithm and the manually fixed one.

Then, the final measurement concerned the vertebral morphometry and its percentage of error, again referring to the manual estimation as the gold standard.

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3. RESULTS AND DISCUSSION

The first algorithm output was the detection of vertebrae, whose accuracy was really important since the subsequent algorithm step was based on this first result. Among the 50 patient radiographs, 260 vertebrae were globally counted.

Our automatic approach missed 35 of the 260 actual vertebrae (13.5%), therefore sensitivity was 86.5%. Furthermore, we obtained a perfect specificity of 100%, because no false positives were present.

The explanations of misdetections were revealed by the analysis of the images. In some cases the vertebrae were located on the image border, i.e. part of the vertebra was outside the image field of view. A possible way to solve the problem is to connect the two detected parts of a vertebral border outside the image field of view by using a contour closing technique based on proximity and curvature characteristics.

In other cases misdetections occurred in very low contrast areas or in particularly high brightness areas.

Anyhow, the reported sensitivity can be labelled as a good result, especially if we take into account that our method performed well also in difficult situations like the one reported in Fig. 3. For all the 225 detected vertebrae, using the ASM method we found the borders, then we localized on these borders the four corners of the vertebra (P1, P2, A1, and A2) and the middle points M1 and M2, as previously described.

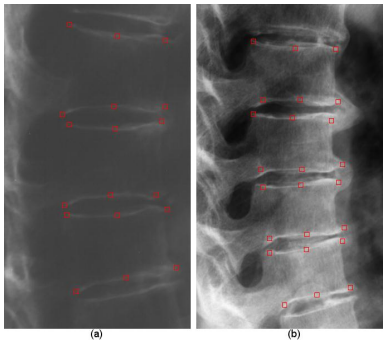

Figure 3. Vertebrae localization. Examples on a low contrast X-ray image (a), and on a good quality X-ray image (b). Red squares indicate the positions of the six characteristic points found on each vertebra by the automatic approach.

The reference point positions found by our automatic algorithm were compared to those manually placed by the radiologist as described in the methodology section.

The mean and the standard deviation of errors were reported in percentage in Table I.

Finally, the ultimate goal of our work was to assess the accuracy of the vertebral morphometry.

The six ratios of the Melton approach were calculated for both automatic and manual methods for all the 225 detected vertebrae and, the relative error was determined as follows,

$$error(R) = \frac{|R_{auto} - R_{hand}|}{R_{hand}} \qquad (2)$$

Table I. Errors in Localization of Vertebra Reference Points [mm]

	P1	P2	M1	M2	A1	A2
Mean	0.82	1.72	2.81	2.57	2.15	2.04
Standard deviation	1.07	2.10	1.79	0.70	2.01	2.31

where R represents one of the six ratios. Obtained results are reported in Table II. The adoption of the Melton approach implied that a threshold of 85% of the normal reference ratio was used to define vertebral deformity [11,12].

The results of our approach compared with the manual method (Table I) showed that our algorithm positioned with high accuracy the points on the vertices (P1,A1,P2,A2) of the vertebra, while larger deviations occurred at the midpoints (M1,M2). This can be explained because our algorithm positioned the midpoints at equal distance from P1 and A1 and from P2 and A2, making it more accurate than a manual approach. Therefore, the calculated errors in midpoint placement should not be strictly considered as actual algorithm errors, but could be more likely due to an intrinsic lower accuracy of the manual placement.

Table II and Table III show that the highest average error occurred on the biconcave deformity (ratio Hm/Hp). By investigating the individual X-ray images, it can be seen that our method considered some patients as "borderline" (i.e., between 0.85 to 0.89), while manual measurements considered them as "non-fractured" but close to the threshold (between 0.83 to 0.84).

Table II. Vertebral Morphometry Error [%]

	wedge *Ha/Hp*	**bi-concave** *Hm/Hp*	**crush post -1** *Hp/Hp(-1)*	**crush post +1** *Hp/Hp(+1)*	**crush ant -1** *Ha/Ha(-1)*	**crush ant +1** *Ha/Ha(+1)*
m	5.17	6.19	1.14	1.03	1.06	5.57
sd	1.81	1.60	0.86	0.26	0.82	2.96

m and sd stand respectively for mean and standard deviation.

Table III reports a synthesis of the vertebral morphometry results obtained by our automatic approach and by the radiologist. The two techniques differed in an appreciable manner only for the "crush ant +1", but for both the value exceeded the threshold of 0.85, therefore the diagnosis resulted anyway unaffected. For all the other considered cases, we can say that the values of mean and standard deviation obtained from the two different methods were very similar to each other.

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Table III. Vertebral Morphometry Results for Automatic (A) and Manual (M) Measures

	wedge *Ha/Hp*	**bi-concave** *Hm/Hp*	**crush post -1** *Hp/Hp(-1)*	**crush post +1** *Hp/Hp(+1)*	**crush ant -1** *Ha/Ha(-1)*	**crush ant +1** *Ha/Ha(+1)*
m A	0.78	0.89	1.00	1.21	1.00	1.12
sd A	0.12	0.11	0.10	0.11	0.18	0.18
m M	0.81	0.84	0.99	1.22	0.99	1.02
sd M	0.16	0.15	0.08	0.08	0.18	0.15

m and sd stand respectively for mean and standard deviation.

4. CONCLUSION

We proposed a novel method for fully automatic vertebral morphometry, which is based on the employment of local phase symmetry measures and an Active Shape Model and is able to work properly also on radiographic images of low quality and contrast, achieving good results. The main source of error was represented by the low symmetry measure obtained when the vertebrae were located on the border of the radiographic images and partially outside the image field of view. Other recognition errors occurred when vertebrae were localized in very low contrast areas or in high brightness areas. Nevertheless, our automatic technique resulted to be particularly accurate in vertebra detection (sensitivity = 86.5%; specificity = 100%) and provided morphometric results very close to the corresponding manual measurements performed by a trained radiologist.

The similarity of the results between the automatic and the manual morphometric measurements, coupled with the good performance of our method also in presence of low contrast images, clearly provides the proposed algorithm with a strong potential for a prompt translation into a routine clinical application.

5. ACKNOWLEDGMENTS

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6. REFERENCES

[1] J. A. Kanis, E. V. McCloskey, H. Johansson, C. Cooper, R. Rizzoli, J.-Y. Reginster, “European guidance for the diagnosis and management of osteoporosis in postmenopausal women”, Osteoporos Int, vol. 24, pp. 23-57, 2013.

[2] C.M. Klotzbuecher , P.D. Ross , P.B. Landsman , T.A. Abbott , 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, April 2000.

[3] G. Guglielmi, D. Diacinti, C. Van Kuij, F. Aparis, C. Kresta, J.F. Adams, T.M. Link, “Vertebral morphometry: current methods and recent advances”, Eur. Radiol. Vol. 18, pp. 1484-1496, 2008.

[4] S. Casciaro and L. Massoptier, “Automatic vertebral morphometry assessment.”, Conf Proc IEEE Eng Med Biol Soc, pp. 5571 – 5574, August 2007.

[5] D. Štern, V. Njagulj, B. Likar, F. Pernuš, T. Vrtovec, “Quantitative vertebral morphometry in 3D”, Proc. SPIE, vol. 8669, March 2013.

[6] D. Diacint and G. Guglielmi, “Vertebral morphometry”, Radiol Clin North Am, vol 48, pp. 561-575, May 2010.

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

[8] 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, September 2005.

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

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

[11] M. A. Adams and P. Dolan, “Biomechanics of vertebral compression fractures and clinical application”, Archives of Orthopaedic and Trauma Surgery, vol.131, pp. 1703-1710, December 2011.

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

[13] D. Alexandru, and W. So, “Evaluation and Management of Vertebral Compression Fractures”, Perm J, vol. 16, pp. 46–51, 2012.

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

[15] T.F. Cootes, C.J. Taylor, D.H. Cooper, J. Graham, "Active shape models - their training and application", Computer Vision and Image Understanding vol 61, pp. 38–59, 1995.

[16] M. Benjelloun, S. Mahmoudi, Fabian Lecron, “A Framework of Vertebra Segmentation Using the Active Shape Model-Based Approach”, Int J Biomed Imaging, vol 2011, July 2011.