A review of methods for quantitative evaluation of axial vertebral rotation

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Abstract Quantitative evaluation of axial vertebral rotation is essential for the determination of reference values in normal and pathological conditions and for understanding the mechanisms of the progression of spinal deformities. However, routine quantitative evaluation of axial vertebral rotation is difficult and error-prone due to the limitations of the observer, characteristics of the observed vertebral anatomy and specific imaging properties. The scope of this paper is to review the existing methods for quantitative evaluation of axial vertebral rotation from medical images along with all relevant publications, which may provide a valuable resource for studying the existing methods or developing new methods and evaluation strategies. The reviewed methods are divided into the methods for evaluation of axial vertebral rotation in 2D images and the methods for evaluation of axial vertebral rotation in 3D images. Key evaluation issues and future considerations, supported by the results of the overview, are also discussed.

Keywords Spine · Axial vertebral rotation · 2D images · 3D images · Review of methods

Introduction

Axial vertebral rotation, defined as the rotation of a vertebra around its longitudinal axis when projected onto the transverse image plane, is among the most important

parameters for the evaluation of spinal deformities [82]. Its quantification is important for planning [5, 87] and analysis [51, 55, 72] of orthopedical surgical procedures; however, current treatment techniques are not based on its precise identification. Precise measurement of axial vertebral rotation is most valuable for the determination of reference values in normal and pathological conditions [22, 78] and, as a result, for a better understanding of the mechanisms of the progression of the deformities [79, 84]. However, routine quantitative evaluation of axial vertebral rotation from medical images is difficult and error-prone due to the limitations of the observer (e.g., non-systematic search patterns), characteristics of the observed vertebral anatomy (e.g., similarity of normal and pathological structures, natural biological variability of the structures) and specific imaging properties (e.g., the presence of image noise, characteristics of imaging techniques, variable patient positioning).

In the past decades, advances in medical imaging technology and computerized medical image processing led to the development of new three-dimensional (3D) imaging techniques that have become important clinical tools in modern diagnostic radiology and medical health care. Although two-dimensional (2D), especially radiographic (X-ray) images are still widely used in clinical examination due to relatively low image acquisition costs and wide area of application, they are persistently being replaced by 3D images. The continuous increase in the number of acquired cross-sections, reduction in cross-sectional thickness and relatively short acquisition times are some of the main reasons for the expansion of 3D imaging techniques. Medical images represent nowadays an indispensable part of modern medical examination and treatment. As a result, the number of medical images is continuously increasing. The methods for quantitative evaluation of medical images

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are therefore most valuable when they are completely automated or require minimal manual intervention. However, the accuracy and reliability of (semi)automated methods have to be verified in order to prove their clinical significance. Quantitative evaluation methods therefore need to be tested on real images and the results compared to reference measurements of the same property. The accuracy and reliability of automated methods should be superior or at least comparable to manual measurements. If the verification of the accuracy and reliability is based on objective criteria, the results of quantitative evaluation are useful for the comparison of measured properties among patients and for the determination of reference clinically relevant values of the measured properties.

The aim of this paper is to provide a complete overview of the existing methods for quantitative evaluation of axial vertebral rotation from medical images, which may provide a valuable resource for studying the existing methods or developing new methods and evaluation strategies. According to the type of evaluated images, we organized the reviewed methods along with all relevant publications under the methods for evaluation of axial vertebral rotation in 2D ([Evaluation of axial vertebral rotation in 2D images](#)) and 3D images ([Evaluation of axial vertebral rotation in 3D images](#)). Final remarks and future considerations are given in Sects. “[Discussion](#)” and “[Conclusions](#)”. For a detailed description and rationale behind the reported degrees of automation (i.e., 1, manual measurement; 2, computer-assisted measurement; 3, computerized image processing; 4, computerized image analysis) and statistical measures for intra- and inter-observer variability of the methods (i.e., RMS, root-mean-square error; MAD, mean absolute difference; SD, standard deviation; *R*, correlation coefficient; ICC, intra- or inter-class correlation coefficient), the reader is referred to our review of methods for quantitative evaluation of spinal curvature [93].

Evaluation of axial vertebral rotation in 2D images

As the rotation of vertebrae in coronal and sagittal planes is often evaluated by spinal curvature [93], the axial (transverse) vertebral rotation is often termed “vertebral rotation”. Various approaches to the measurement of axial vertebral rotation were developed for coronal and axial 2D images, and are summarized in Table 1.

One of the first documented methods for the measurement of axial vertebral rotation in coronal radiographic images was presented by Cobb [20]. The rotation was determined according to the position of the vertebral spinous process relative to the vertebral body. The spinous process is normally located in the middle of the vertebral body; however, with increasing vertebral rotation it moves

Table 1 Evaluation of axial vertebral rotation in 2D images

Method [ref.]	Degree ^a	Reported variability [ref.] ^b
Cobb [20]	1	–
Nash–Moe [64]	1	SD: 4.7° [25] • 4.7° [26] R: 0.77 [40] RMS: 2.2° [18] ICC: 0.63 (man, intra), 0.56 (man, inter) [53] • 0.73 (comp, intra), 0.56 (comp, inter) [52]
Fait–Janovec [33]	1	SD: 3.0° [33] • 6.5° [25] R: 0.75 [40]
Coetsier et al. [21]	1	SD: 6.4° [25] R: 0.90 [40]
Perdriolle [71]	1	R: 0.90 [40] • 0.94 (intra) 0.99 (inter) [94] MAD: 1.0° (intra) 3.0° (inter) [94] • 6° [74] SD: 5.1° [25] • 2.3° [67] RMS: 5.1° [18]
Bunnell [16]	1	SD: 3° [16] • 4° (comp) [77]
Monji–Koreska [63]	1	SD: 5° (comp) [77] • 3.6° [96]
Drerup et al. [25]	1	SD: 5° [25] • 4.8° [26] • 4° (comp) [77] R: 0.77 [40] RMS: 3.6° [18]
Stokes et al. [85]	1	SD: 3.6° [85] • 2° (comp) [77] RMS: 3.1° (man), 2.2° (comp) [18]

^a Degree of automation

^b *Man* manual measurement, *comp* computerized measurement, *intra* intra-observer, *inter* inter-observer

towards one side of the spine curve. The five grades of axial vertebral rotation were determined by dividing the vertebral body into six equal segments and identifying the segment that contained the spinous process (Fig. 1a). Unfortunately, the method could not describe the full range of vertebral rotations that can occur in some forms of pathology, e.g., in scoliosis (i.e., 0°–90°). A similar five-graded method was proposed by Nash and Moe [64], where the rotation was quantified by the position of the vertebral pedicles, which are normally located in the outer parts of the vertebral body, but also move towards one side of the spine curve with increasing vertebral rotation. The grades of rotation were also translated to degrees of rotation by measuring the offset of the inner pedicle center (Fig. 1b). Fait and Janovec [33] proposed a modification to the Nash–Moe method. The outer edge of the inner pedicle shadow was used rather than its center; moreover, the measurements resulted in a pedical offset ratio that was converted to degrees of rotation by using a pre-defined look-up table

Fig. 1 Evaluation of axial vertebral rotation in 2D images. **a** Cobb method [20]. **b** Nash-Moe method [64]. **c** Fait-Janovec method [33]. **d** Coetsier et al. method [21]. **e** Perdriolle method [71]. **f** Bunnell

method [16]. **g** Monji-Koreska method [63]. **h** Drerup method [25, 26]. **i** Stokes et al. method [85]

(Fig. 1c). All of the above-mentioned methods defined the axial vertebral rotation over a single anatomical landmark relative to the vertebral body, i.e., the offset of the spinous process or pedicle. The accuracy of measurements was affected by ignoring the fact that, with increasing vertebral rotation, the radiographic projection of the vertebral body is not constant, resulting in inaccurate measurements of its properties, e.g., width.

Mehta [60] evaluated the axial vertebral rotation on stereo-radiographs, acquired at 15° angular intervals. To overcome the disadvantages of relying on a single anatomical landmark, the author identified the dominant landmark at different rotation angles, i.e., the pedicle at 15°

and 30°, the transverse process at 45° and 60°, and the vertebral body at 75° and 90°. Mehta also proposed simple matching of normal and pathological radiographs as a technique for measuring the rotation in scoliosis. However, already Benson et al. [10] showed that apparent radiographic pedicle movement was not equal to actual pedicle movement, especially when the vertebrae were tilted in the coronal or sagittal plane, and mentioned that the measurement of pedicle position may also be significantly influenced by changes in vertebral shape. Hecquet et al. [42] referred to the rotation that resulted from the vertebral coronal and/or sagittal tilt as the “introduced” rotation, and suggested that it should be considered when the vertebral

tilt exceeds 30° . Instruments for measuring the vertebral rotation angle directly from the radiographic position of the inner edges of both pedicles and from the center of the inner pedicle were designed by Coetsier et al. [21] (i.e., the Ghent rotation measuring device; Fig. 1d) and Perdrille and Vidal [71] (i.e., the torsionmeter; Fig. 1e), respectively. When such instrument was positioned on the radiograph so that it was aligned with the lateral borders of the body of the measured vertebra, the line through the anatomical landmark on the inner pedicle shadow was used to identify the angle of vertebral rotation on the instrument scale. Bunnell [16] proposed a method that was based on the offset of the spinous process relative to the width of the vertebral body (Fig. 1f). A similar method derived the vertebral rotation from the distance of the pedicle centers from the lateral vertebral body borders and the width of the superior vertebral endplate (Fig. 1g). The method remained unpublished by the original authors, but was attributed to Monji and Koreska [63] in a later study [96].

Drerup [25, 26] improved the Nash–Moe method by modifying the measurement of the position of anatomical landmarks, i.e., the projections of vertebral pedicles. By using known pre-defined vertebral shape parameters, namely, the angle from the pedicle to the spinous process and the distance from the pedicle to the vertebral body center, a trigonometrical model to measure axial vertebral rotation was proposed (Fig. 1h). The author stated that vertebral coronal and sagittal tilt did not affect the rotation measurements when they were referenced from the local vertebral and not global radiographic coordinate system. A similar method was presented by Stokes et al. [85], where the position of the pedicles relative to the vertebral body center was combined with known vertebral shape parameters, i.e., the actual distance between the pedicles and the actual distance between the pedicles and the vertebral body center (Fig. 1i). The accuracy of the vertebral rotation measurements was improved, which was probably due to the fact that the measurements were performed in a coronal and a 15° oblique coronal radiograph.

Gunzburg et al. [40] studied five different methods for measurement of axial vertebral rotation in lumbar spine radiographs. Among the Nash–Moe, Fait–Janovec, Coetsier et al., Drerup et al. and Perdrille method, the latter was reported to be the most accurate for measuring rotations of up to 30° . Other studies reported similar findings [8, 67, 94] and suggested that, in order to minimize measurement errors due to improper patient positioning, the rotation of a reference vertebra should be measured besides the rotation of the vertebra at the apex of the spine curve. On the other hand, Richards [74] reported that precise measurements of vertebral rotation with the Perdrille torsionmeter should not be expected, especially due to obstruction of anatomical landmarks by metal implants,

difficulties in precise marking of the pedicle and further variations caused by patient positioning. Most of the above-mentioned studies also reported that the torsionmeter significantly overestimated the actual vertebral rotation. Russell et al. [77] evaluated the computerized implementations of the Bunnell, Drerup, Monji–Koreska and Stokes et al. method in the radiographs of one thoracic and one lumbar vertebra. They reported the Stokes et al. method to be the least accurate, probably because the range of values the vertebral rotation angle can achieve is limited by the proposed equation, while the other three methods gave similar results, with the Bunnell method being slightly superior in all aspects. The authors also emphasized that the accuracy of the measurements depended highly on the ability to mark the anatomical landmarks in the radiographs. Chi et al. [18] assumed that the Stokes et al. distance between the pedicles was not a reliable vertebral shape parameter, because it was projected onto the radiograph and therefore altered with vertebral rotation. As an alternative, they proposed a computerized method, where the projected distance between the pedicles was iteratively updated until it converged to a final value. They also compared the rotation measurements of lumbar vertebrae with the Nash–Moe, Drerup, Stokes et al. and Perdrille method. The Stokes et al. method was again reported to produce significantly large errors, while the Perdrille torsionmeter method was found easy to operate with. In two recent studies of Kuklo et al. [52, 53], moderate to good intra- and inter-observer reliability was reported in the analysis of manual measurements of apical vertebral rotation with the Nash–Moe method in analog [53] and digital [52] radiographs.

The analysis of the performance of the proposed methods [27, 28, 44, 67, 77, 79, 94] proved that the assessment of axial vertebral rotation from coronal radiographic images is unreliable, which is mostly because the radiographic projections do not provide sufficient quantitative or enough qualitative information of the observed anatomical structures.

Evaluation of axial vertebral rotation in 3D images

In order to improve the accuracy of the measurements, the evaluation of axial vertebral rotation was approached by methods developed for 3D spine images. The reviewed methods with the assigned degrees of automation and reported reliability and/or repeatability are summarized in Table 2.

The evaluation of axial vertebral rotation was first approached by stereophotogrammetric reconstruction of vertebrae in 3D using either biplanar orthogonal [15, 59, 70] (Fig. 2a) or biplanar oblique [54] radiography. As the

Table 2 Evaluation of axial vertebral rotation in 3D images

	Method [ref.]	Degree ^a	Reported variability [ref.] ^b
	3D reconstruction methods	2	RMS: (φ_a , φ_c , φ_s) = (1.9°, 1.9°, 1.0°) [30] MAD: 1.9°–4.0° [59] SD: 3.6° [86] • 1.2°–2.4° [27, 29] • (φ_a , φ_c , φ_s) = (6.4°, 3.6°, 3.7°) [73] • 0.9° (intra), 1.0° (inter) [36]
	Aaro–Dahlborn [1]	1	MAD: 0.6°–2.0° [1] • 0.5° [2] SD: 1.6° [44] • 1.6° [50] • 1.8° (intra), 4.7° (inter) [37] • 2.8° (intra), 2.6° (inter) [2]
	Ho [44]	2	MAD: 2.6° (intra), 3.0° (inter) [13] • 0.7° [2] SD: 1.2° [44] • 1.3° (intra), 1.9° (inter) [45] • 1.3° [12] • 1.2° (intra), 2.4° (inter) [37] • 3.3° (intra), 2.4° (inter) [2]
	Krismmer et al. [50]	1	SD: 2.2° [50] • 3.3° (intra), 6.1° (inter) [37]
	Göçen et al. [38]	1	SD: 1.1° (intra), 1.8° (inter) [38]
	Haughton et al. [41]	4	SD: 0.9° (man), 0.2° (comp) [75] • 0.1° [76]
	Adam-Askin [2]	4	MAD: 0.25° [2]
	Kouwenhoven et al. [48]	4	ICC: 0.99 (intra), 0.96 (inter) [49] • 0.91 (intra), 0.87 (inter) [48]
^a Degree of automation	Vrtovec et al. CT [90]	4	–
^b <i>Man</i> manual measurement,	Vrtovec et al. MR [91]	4	SD: 0.9° [91]
<i>comp</i> computerized	Vrtovec et al. CT & MR [92]	4	RMS: (φ_a , φ_c , φ_s) = (0.53°, 0.53°, 0.58°) [92] SD: (φ_a , φ_c , φ_s) = (0.26°, 0.26°, 0.28°) [92]
measurement, <i>intra</i> intra- observer, <i>inter</i> inter-observer			

obtained radiographs are actually 2D, but their combination allows the extraction of 3D structural information, such techniques are often termed two-and-a-half-dimensional (2.5D). By identifying the same anatomical landmarks on vertebrae in both coronal and sagittal radiographs, the vertebrae were reconstructed in 3D and their position and rotation were studied. The inferior bases of pedicles and the centers of vertebral endplates proved to be reliable landmarks, visible in both views along the whole spine [15, 59, 70, 81]. A number of studies investigated the accuracy and precision of the reconstruction of vertebrae in 3D with different density of reconstructed points [3, 4, 30, 36, 61, 62, 73]. It was reported that the evaluation of axial vertebral rotation by 3D reconstruction was much more accurate than by any other method [36]; moreover, 3D reconstruction allowed straightforward segmental angulation analysis [7, 31, 34]. However, to preserve a precise 90° angle between the coronal and sagittal radiograph, particular attention had to be given to patient positioning.

Although the measurement of axial vertebral rotation in axial cross-sections is considered to be the most intuitive approach, it only became possible with the development of 3D imaging techniques. One of the first methods for measuring axial vertebral rotation in axial CT cross-sections was proposed by Aaro and Dahlborn [1]. The rotation was determined by the angle between the line that connected the point at the posterior junction of the two laminae

of the vertebral arch with the center of vertebral body, and the reference sagittal plane (Fig. 2b). Unless the vertebral tilt in both sagittal and coronal planes exceeded 20°, high accuracy of the method was reported. Without further investigation, the Aaro–Dahlborn method was adopted as a standard in a number of studies [32, 57, 78]. Yazici et al. [98] compared Aaro–Dahlborn measurements in axial CT cross-sections with Perdriolle torsionmeter measurements in coronal radiographs, acquired in patient supine and standing position, respectively. They reported that the torsionmeter gave as accurate results as the Aaro–Dahlborn method, which could be useful to determine the magnitude of the deformity in standing position, and that the influence of patient positioning could be considered as an additional rotation of vertebrae in 3D. Kuklo et al. [51] compared the Aaro–Dahlborn method to the Nash–Moe and Perdriolle method, and reported that both radiographic techniques were subjected to variability; moreover, they significantly overestimated the actual vertebral rotation. Kojima and Kurokawa [47] proposed to represent a 3D spinal deformity with a rotation vector. The direction of the rotation vector was equal to the direction of the vertebral rotational axis, while its length was equal to the rotation angle around the rotational axis.

A method similar to the Aaro–Dahlborn method was proposed by Ho et al. [44]. The angle, defined between the two lines that connected the junction of each lamina and

Fig. 2 Evaluation of axial vertebral rotation in 3D images. **a** Biplanar orthogonal radiographic reconstruction method [15, 59, 70]. **b** Aaro-Dahlborn method [1]. **c** Ho et al. method [44]. **d** Krismer et al. method [50]. **e** Göçen et al. method [38]. **f** Haughton et al. method [41].

g Adam–Askin, method [2]. **h** Kouwenhoven et al. method [48]. **i** Vrtovec et al. CT method [90]. **j** Vrtovec et al. MR method [91]. **k** Vrtovec et al. CT and MR method [92]

the pedicle with the posterior junction of the two laminae, was first bisected by a third line. The angle of axial vertebral rotation was then measured as the angle between the obtained line and the reference sagittal plane (Fig. 2c). The authors compared the proposed method to the Nash–Moe method, evaluated in supine coronal CT cross-sections, and reported that the Nash–Moe method overestimated the actual vertebral rotation angle [45]. Birchall et al. [13] applied the Ho et al. method to cross-sections that were

obtained from MR images by multiplanar reformation through the vertebral endplates. In a later study [12], the same technique was used to evaluate the rotation and mechanical torsion between vertebral endplates in MR images.

Krismer et al. [50] proposed a more complex method for measurement of axial vertebral rotation in CT images. The method was based on the identification of five distinctive points, namely the points at the vertebral body center, at

the tip of the spinous process, at the center of the spinal canal between both laminae, and at the most anterior and posterior parts of the spinal canal, respectively. The points served to form lines that determined different axial rotation angles, measured against the reference sagittal plane (Fig. 2d). The authors also reported that measurement errors may occur when the vertebrae were completely symmetrical and when the measurements in axial cross-sections were replaced with measurements in oblique cross-sections. Göçen et al. [37] evaluated the Aaro–Dahlborn, Ho et al. and Krismer et al. method, and reported that the main problem of the Aaro–Dahlborn method was in unclearly defined anatomical landmarks. On the other hand, the line bisecting the angle formed by two laminae in the Ho et al. method represented a very reliable reference line. They concluded that the Ho et al. method was the most reliable and clinically useful, while the Krismer et al. method was the least reliable but potentially useful in measuring the rotation within vertebrae. The same authors also proposed a new method [38], where the axial vertebral rotation was defined by the angle between the line that connected the most posterior points of the two pedicles, and the reference sagittal plane in an axial CT cross-section (Fig. 2e).

Although the above-mentioned methods were defined by exact anatomy-based procedures and measured the axial vertebral rotation in 3D images (i.e., CT or MR), the measurements were still performed in 2D (i.e., in axial cross-sections) and therefore can not be considered as 3D measurements. Due to spinal deformities, the vertebrae may also be rotated in sagittal and coronal planes, resulting in measurement errors in the form of an induced “virtual” axial rotation [50, 98]. Skalli et al. [79] compared the measurements in 3D with the measurements in 2D, and concluded that the determination of axial vertebral rotation in axial cross-sections could be inaccurate, especially in the case of strong sagittal or coronal vertebral tilt. Although the patients are exposed to additional radiation, the CT proved to be the most accurate imaging technique for the determination of axial vertebral rotation [50, 51]. However, problems of finding reliable landmarks and neutral reference lines remained. On the other hand, the accuracy of measurements in MR images is limited by image resolution, signal-to-noise ratio, and distortions caused by metal implants.

In the past few years, the measurement of axial vertebral rotation was approached by computerized methods and methods based on image analysis techniques, although manual determination of the initialization parameters was still required. The method proposed by Haughton et al. [41, 75] required manual selection of the axial MR cross-section, manual determination of the vertebral center of rotation and manual determination of the circular area that

encompassed the measured lumbar vertebra. After initialization, the method automatically measured the vertebral rotation relative to the cross-section of a second vertebra by searching for the maximal correlation of image intensities between the circular areas that encompassed the vertebrae in both cross-sections (Fig. 2f). Besides in MR images, the same method was used also in CT images [76]. Oblique CT cross-sections were used by Adam and Askin [2], who determined the axial vertebral rotation as the orientation angle of the straight line that bisected the thresholded image of the vertebral body. The line orientation angle was obtained from the symmetry ratio, defined by the maximal correlation of image intensities in the bisected regions (Fig. 2g). By comparing their computerized method to manual measurements using the Aaro–Dahlborn and Ho et al. method, they claimed the method to be insensitive to image thresholding, which was not in accordance with the reported 2.8° change in vertebral rotation due to different threshold values. Kouwenhoven et al. [48] applied an image analysis based method to measure vertebral rotation in manually selected axial cross-sections, determined through the centers of vertebral bodies in CT and MR [49] images of normal spines. An automatic region growing segmentation technique was first used to obtain reference vertebral points, such as the center of the vertebral canal, the center of the sternum at the T5 vertebra, and the center of the anterior half of the vertebral body. The rotation was then defined as the angle between the line through the center of the vertebral canal and the anterior half of the vertebral body, and the line that connected the center of the vertebral canal with the sternum at the T5 vertebra (Fig. 2h). Axial vertebral rotation was studied in both CT and MR images of whole spines also by Vrtovec et al. In CT images [90] (Fig. 2i), circular cross-sections were first automatically extracted from 3D images so that they were always orthogonal to the spine at an arbitrary position on the spine. The rotation in each cross-section was then defined with the line that bisected the cross-section and resulted in the maximal correlation of image intensities in the bisected regions. The rotation values in different cross-sections were finally connected by a polynomial function, which resulted in a continuous and smooth description of axial vertebral rotation along the whole spine. For MR images [91] (Fig. 2j), the rotation was defined in an optimization procedure that searched for the orientation angle of the straight line of symmetry in each axial cross-section, and then smoothed with a polynomial function along the whole spine using the least-trimmed-squares regression technique. The same authors also combined both approaches into a method that was modality-independent, i.e., applicable to both CT and MR images [92] (Fig. 2k). Basing on the known location of the vertebral body center in 3D, they obtained the relation between the image and

vertebral coordinate systems by matching image intensity gradients that defined the best available symmetry of the vertebral anatomical structure. Besides the axial rotation, the coronal and sagittal vertebral rotations were determined simultaneously with a total reported accuracy and precision of around 1.0° and 0.5°, respectively.

Discussion

From the clinical point of view, precise measurement of axial vertebral rotation is not of utmost importance for the treatment of spinal deformities, as it is not required by current treatment techniques. On the other hand, precise measurement of axial vertebral rotation is most valuable for classification purposes, e.g., for the determination of reference values in normal and pathological conditions, or for a better insight to the progression mechanisms of the deformities. A recent study of manual radiographic measurements of different spine parameters, among them the axial vertebral rotation, showed that the parameters may be measured with low error between trials or between observers, but rarely both, and with more confidence on coronal than sagittal radiographs [23]. Moreover, the study reported that the measurements performed in analog radiographs do not provide valuable information as they are not reproducible and reliable. Although manual measurements were the only option in the past due to a limited availability of imaging technology, they are nowadays considered unreliable. Methods for manual measurements are often too complex for routine clinical use and the inter- and intra-observer variability is always present because of the bias of the observer and the inability of the observer to repeat multiple measurements of the same parameter, respectively. Moreover, with the increasing number of medical images and current advances in imaging and image analysis techniques, manual measurements have become relatively ineffective as they represent a very time-consuming task. On the other hand, the results of a computerized method are always equal once the required settings are determined for the selected image. Avoiding manual settings determination therefore represents the most challenging task in the development of computerized methods, and solutions to this problem were already proposed by applying automated image processing and analysis techniques for the evaluation of axial vertebral rotation [2, 41, 48, 49, 75, 76, 90–92]. By increasing the efficiency in the interpretation of images, computerized methods improve the reliability and repeatability of such evaluation. Methods of computer-assisted diagnosis (CAD) are constantly being developed to aid in the interpretation of the increasing amount of medical image data and clinical information [35], and have therefore become one of the

major research topics in medical imaging and diagnostic radiology.

Over the past years, MR has become a more dominant modality in spine imaging, providing high-quality 3D images of soft tissues and bone structures of the spine by a correct selection of imaging parameters. MR is considered to be the modality of choice for follow-up examinations and longitudinal studies. However, because metal objects cause distortions in the acquired images, the MR will never be the modality of choice for patients with metal implants. Such distortions are less severe in the case of CT imaging; however, the CT technique is less appropriate due to additional patients' exposure to radiation. Although 3D images proved to be the most accurate imaging technique for the determination of axial vertebral rotation [50, 51], one of the main limitations of the reviewed methods is that the measurements are performed in 2D cross-sections which are extracted from 3D images. As a result, the observed anatomical structures represent only a projection of the actual 3D vertebral anatomy, which induces additional errors in the quantitative evaluation of axial vertebral rotation. Some studies attempted to overcome this limitation by introducing the vertebral coordinate system [6, 14, 72, 92]; however, it required exact manual identification of distinctive vertebral anatomical landmarks, e.g., the centers of vertebral body endplates, the bases of both pedicles, or the center of the vertebral body in 3D, thus introducing observer variability. Another drawback of many studies is the insufficient comparison between different methods. Moreover, different studies apply different statistical measures of the reliability and reproducibility of a method. As a result, it is often impossible to convert between different measures and further compare different studies, which was also a limitation we encountered when preparing this review. Nevertheless, the concept of evaluating the axial vertebral rotation quantitatively suffers from one general shortcoming. It is, namely, impossible to uniquely define reference values that would represent the “gold standard” vertebral rotation. Even for a healthy anatomy, the vertebral structures are not perfectly symmetrical and therefore the determination of the orientation of the vertebral spinous process, transverse processes, pedicles or vertebral body in 3D may be ambiguous. Identifying anatomical landmarks prior to image acquisition (e.g., markers on cadaveric spines) would not solve this problem, as the selection of such landmarks would considerably influence the measurements. A partial solution to this problem may exist in the form of an image database, annotated with different methods that would allow comparison between existing methods and aid in the development of new methods. If such a database would be adequately anonymized, publicly available, and consist of different imaging modalities (e.g., radiographic, CT and MR images), normal

Fig. 3 Summary of the reviewed methods. **a** The number of manual methods (degree of automation 1 & 2) versus the number of automated methods (degree of automation 3 & 4). **b** A timeline showing the cumulative number of the proposed manual (degree of automation 1 & 2) and automated methods (degree of automation 3 & 4)

and pathological vertebrae, it would definitely represent a valuable contribution to the research community.

In this review, we have summarized the existing methods for quantitative evaluation of vertebral rotation from medical images of the vertebrae. According to the defined degrees of automation [93], we can further attribute the methods to two basic groups. The group of manual methods consists of methods that are completely manual (degree of automation 1) or performed by computerized measurements of manually identified landmarks (degree of automation 2). On the other hand, the group of automated methods consists of methods that utilize image processing (degree of automation 3) or image analysis (degree of automation 4) techniques. A computerized implementation of a manual method was not considered as a new method; however, such occurrences were very rare. Most of the reviewed methods belonged to the first group (Fig. 3a), mostly because the first manual method was proposed in 1948, while an automated method was not proposed until 2002 (Fig. 3b). The fact that the number of manual methods has been increasing even after the appearing of automated methods indicates that the possibilities of quantitative evaluation of vertebral rotation have not been entirely explored yet and that there is still much room for improvements. Furthermore, this may also indicate that new methods are primarily developed by clinicians. Unfortunately, from the reviewed publications it is not possible to draw firm conclusions on which method is the most useful from the practical or clinical point of view. For the measurement of axial vertebral rotation in coronal radiographs, the torsionmeter proposed by Perdriolle and Vidal [71] was generally shown as the most accurate [8, 40, 67, 94, 98] and simple for use [18]. For 3D images, the Ho et al. method [44] proved to be the most reliable and clinically useful [37], moreover, it was successfully applied to both CT and MR spine images [12, 13]. However, in order to develop an effective image-based yet clinically relevant measure of axial vertebral rotation in 3D, a strong coupling of the clinical knowledge in anatomy and engineering expertise in computerized image analysis may result in a successful combination.

Conclusion

The methods for quantitative evaluation of axial vertebral rotation are not limited only to measuring actual values, but also provide valuable support in various vertebra-related studies, e.g., in the field of vertebral morphometry [24, 39, 56, 58, 65, 69, 80, 88, 89], biomechanics [19, 66, 83, 95], fusion of radiographic, CT and MR vertebral images [17, 68], vertebrae reconstruction [9, 11, 46], or vertebra segmentation [43, 97]. The advances in medical image processing, analysis and understanding therefore represent valuable support for computerized quantitative evaluation of axial vertebral rotation in 3D that may further improve medical diagnosis, treatment and management of spinal disorders.

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Conflict of interest statement None.

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