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Scoliosis quantification: an overview

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Scoliotic curvatures have long been a focus of attention for clinicians and research scientists alike. The study, treatment and ultimately, the prevention of this prevalent health condition are impeded by the absence of an accurate, reliable, convenient and safe method of scoliosis quantification. The purpose of this paper is to provide an overview of the current methods of scoliosis quantification for clinicians who address this condition in their practices.
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KEY WORDS: scoliosis, measurement, curve.

Depuis longtemps, les courbures scoliotiques attirent l'attention des cliniciens et des chercheurs. L'absence d'une méthode d'évaluation de la scoliose précise, fiable, pratique et sans risque freine l'étude, le traitement et la prévention de cette anomalie répandue. Cet article vise à donner aux praticiens qui doivent traiter cette malformation un aperçu des méthodes courantes d'évaluation.
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MOTS CLÉS : scoliose, estimation, courbure.

Introduction

Scoliotic curves have long been a focus of attention for clinicians and research scientists who have an interest in the musculoskeletal and/or other body systems. It is known that scoliotic curves can range from mild, benign deviations which have considerable prevalence to large, painful, life-shortening deformities afflicting fewer than 1% of the population.[1] As a result of the morbidity and mortality associated with the severe forms of scoliosis, attempts have been made throughout history to assess and treat this condition. These attempts have generally been unsuccessful for a variety of reasons. Firstly, health science is generally unable to identify who will develop scoliosis or consistently predict the rate at which any one curve will progress.[2] Secondly, in over 80% of scoliotic cases, the etiology of the curvature can not be identified.[3] It is the opinion of the authors that the most significant limitation in the study and treatment of scoliosis is that an accurate, reliable, convenient and completely safe form of scoliosis quantification does not currently exist. Therefore, the ability to answer specific questions regarding the prevalence, natural history, or efficacy of various treatments as they relate to scoliosis is ultimately stifled by an inability to effectively and reliably measure the problem.

The purpose of this paper is to review the current methods of scoliosis mensuration for clinicians who address scoliosis in their practices. Based on this information, the current status and future direction of scoliosis quantification will be discussed.

Why is scoliosis difficult to quantify?

It has been traditional to define scoliosis as an undesirable, lateral deviation of the spine. In reality, scoliosis is a condition which may consist of rotation, translation and migration of the vertebral column into the lateral and other spatial planes. Additionally, scoliosis not only affects the spine, but also may have anatomical and physiological relevance at the level of individual vertebrae or the entire body. Specifically, it is these multi-dimensional and multimodal qualities which make scoliosis so difficult to quantify; there is no particular method of measurement which is able to simultaneously and directly address all of the important aspects of the condition. As a result, numerical values thought to quantify scoliosis do not adequately rep-

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resent the actual phenomenon. Issues of cost, availability and risk also add to the difficulty of assessing scoliosis.

Non-Imaging, clinical and/or qualitative methods

The most common procedure used in the clinical assessment of scoliosis is the forward flexion test.[4,5,6] The forward bending test is based on the observation that scoliotic curves often create spinal asymmetries which when large enough, manifest themselves in the adjacent spinal tissues. On forward flexion, asymmetries in spinal alignment are magnified and often are seen as a "rib hump" or other such deviations. It has been estimated that with trained personnel, the forward flexion test can detect curves of 5–10° as measured by a common radiological procedure[2] (Cobb Angle) versus a detection threshold of 25° for a subject in a standing, neutral position[5] and of 44° when left to the detection of family members.[2] Based on these detection rates, its ease of application, cost and low risk to the patient, the forward flexion test has become the standard method of screening populations for scoliosis.[6,7]

The forward flexion method, like other clinical methods, relies on the assumption that the musculoskeletal system associated with the scoliosis will reflect the extent of the condition in some linear relationship. This is not the case however. Clearly, the sensitivity and specificity of the test is poor unless curves of a relatively large magnitude are examined.[8] Even when curves are large and easily detected by forward flexion, the test is not a quantitative one: it can not generate a measurement. At best, the forward flexion test can be used as a screening tool as it is safe, cheap and easy to employ while actual curve quantification must come from other methods.

As the forward flexion test is safe, easy to use and inexpensive, attempts have been made to try to quantify the results of the test by developing instruments which assess spinal asymmetries during forward flexion. The most well known and frequently studied of these instruments is the scoliometer.[9] This device utilizes a gravity-dependant indicator to determine the angulation of the spine with respect to the horizon as the instrument rests across the midline at full forward flexion. Studies which have investigated such devices are often contradictory in their conclusions regarding the reliability of these instruments and the correlation of the measurements to a gold standard.[10–13] This level of performance has lead to the speculation that the use of such instruments results in a high false positive detection rate.[5] As a result, recommendations for the use of such instruments are varied.

Contour Assessment

Observers of the spine have historically noted a relationship between the contour of the back and the geometry of the spine when a subject is in an upright position. Contemporarily, the exact nature of this relationship has yet to be defined.[14] Despite this lack of understanding, a sophisticated category of instrumentation has evolved to assess upright back contour as it may or may not relate to scoliosis.

The most basic of these devices have been pantographs, devices first used in the reproduction of art, text and machinery. A pantograph is made up of a linkage system which when one end is physically traced on the source object, the opposite end reproduces the movement at various magnifications. This type of device has been used to "trace" the surface of the spine resulting in a type of contour map.[15] Recently, advanced electronics have allowed the development of instruments which characterize the three dimensional coordinates of discrete anatomical points (Faro Medical Technologies, Montreal). While these types of instruments may have reasonable reliability and accuracy in very controlled conditions, clinical measurements perform more poorly and do not appear to relate to measures obtained from imaging techniques.[16] Other, similar, instruments have been utilized which assess vertebral positioning through very direct topographical methods. Labelle et al.[17] have developed an instrument which is inserted into a surgically-drilled hole in the spinous process of subjects undergoing surgery. While not a clinically useful instrument, the ability of this device to directly assess vertebral position independently of surface topography makes it possible to provide ongoing estimates of vertebral orientation during surgical correction procedures.

Another method of scoliosis assessment based on surface contour analysis is Moiré topography. This method relies on the Moiré effect; when light is viewed between two structures of equal, but phase shifted frequencies, lines of interference, or Moiré fringes, are created. Clinically, the creation of Moiré patterns is achieved by shining a high powered light through a wire grid onto a subject's back. Moiré fringes are produced from the interaction of the grid and the shadow of the grid. These fringes are analogous to contour lines on a seismic map and have been shown to correspond to alterations of approximately 5.0 mm in surface height.[18] When used on the human back, asymmetries in spinal contour are noted by the presence of deviations in the fringe pattern from left to right. It is thought that methods such as Moiré topography provide ways to quantify scoliosis more accurately and sensitively than observational methods (i.e. forward flexion tests) but without the risks associated with radiological methods.

Although a number of studies exist which support the use of Moiré analysis,[19,20,21] many studies conclude that Moiré methods are problematic.[22,23,24] Typically, Moiré methods are negatively affected by surface alterations caused by the scapulae as scapulae can be asymmetrical in a variety of ways while the spine remains normal. This phenomenon creates the hallmark of Moiré topography which is a high rate of false positive detection. While some studies have shown that Moiré topography can determine the presence, side of convexity and location of scoliosis[25], this can generally be determined with the forward flexion test.[26] Attempts to correlate Moiré results with measurements of spinal curvature obtained from direct imaging methods show that Moiré methods are less able to identify apical vertebrae and correlate poorly to the degree of curvature as measured by radiological methodology.[22,23,24]

Recently, improvements to the Moiré method have been studied which claim to reduce the variability of the measure.[18] Additionally, other more advanced methods of contour scanning (light-based, opto-electric methods)[14,27] have been developed. While these techniques offer certain improvements, the authors are unaware of any study which has investigated the relationship between topographical variables (i.e. body mass index, muscular asymmetry) and their effect on assessing spinal alignment. Despite the refinement and advancement of methods to assess the topography of the spine, the relationship between surface contour and spinal deformity is not understood.

Quantitative methods based on two dimensional imaging techniques

Plain film investigations

Plain film radiographs have become the standard for assessing musculoskeletal pathology, including the quantification of scoliosis[28] as the procedure provides a way to directly visualize the anatomy of interest. Today, plain film analysis has become a readily available, cost-effective tool in the quantification of scoliosis. This being the case, a wide range of measurement techniques have been developed to assess musculoskeletal pathology visualized in this manner. Plain film analysis is additionally an advantageous form of scoliosis assessment as the procedure may reveal additional diagnostic information about the subject's condition.[29] While there are obvious and important advantages in utilizing plain film in the assessment of scoliosis, there are several problems with this technique that limit its impact.

Dosage of radiographs

The most obvious problem associated with plain film analysis is that exposure of humans to sources of ionizing radiation may result in the initiation of various carcinogenic diseases. This process is related to the dosage and frequency of exposures. Once diagnosed with scoliosis, radiographic analysis may occur 3–4 times per year over a course of several years providing relatively high doses of ionizing radiation to a patient.[30] Hoffman et al.[31] noted one scoliotic patient who had been examined radiologically over 600 times. It has been suggested that this frequency of exposure, especially in young females, increases the risk of developing breast cancer.[31] While technological advancements have decreased the dosage of radiation required for plain film analysis (tube filters, patient orientation to the incoming beam, digital x-ray equipment), Leavey et al.[30] have shown that the risk of cancer associated with radiological assessment for scoliosis "is not negligible" as there is an increase in risk for developing breast cancer in scoliotic patients who proceed to surgery.

Measures of scoliosis derived from plain film

The advantage of plain film analysis in assessing scoliosis is that the deformity can be directly visualized and therefore, measurement of the deformity itself can be attempted. Various methods have been developed to place markings on radiographs where by direct measurement or by calculation, estimates of curve magnitude are made which are thought to be meaningful. Two common methods of mensuration, the Cobb-Lippmann method and the method of Nash and Moe will be specifically discussed as their strengths and weaknesses are typical of the majority of roentgenometric methods.

The Cobb-Lippman, or Cobb method, is the most common method of assessing the lateral deformity of scoliosis and was first presented in 1948.[32] This method of scoliosis mensuration is the preferred method of scoliotic angulation quantification from plain films.[29] In the Cobb method, lines are drawn parallel to the superior and inferior endplates of the vertebrae which bound the curvature. From these lines, perpendicular lines are drawn and the resulting angle of intersection is measured. This is known as the Cobb angle, or the scoliotic angle.[33] From these same films, the method of Nash and Moe can be used to assess the vertebral rotation that often accompanies scoliotic curves.[34] The pedicles of the vertebrae of interest are identified and then assigned categories of rotation based on their movement from "normal" locations.

Superficially, it would appear that plain film methods of scoliosis quantification are very valuable in that they measure something that appears to be related to the deformity in spite of some potentially detrimental effects. It can sometimes be forgotten that included in these detrimental effects is measurement error. All measures are subject to error, and roentgenometric methods are no exception.

Types of error in roentgenometric assessment of the spine

One category of potential error in measurements derived from plain film comes from the taking of the film itself. Changes of up to 17° in the angle of scoliosis (measured by Cobb method) can occur simply from inconsistent subject positioning prior to exposure.[35] Furthermore, technical inconsistencies in radiographic exposure can generate Cobb angle alterations of up to 9°. The development of standards and subject positioning frames have helped to reduce these errors but their use is far from common.[36]

Any method that identifies anatomical landmarks for measurement purposes is also subject to errors caused by variations of the target landmark itself. The landmarks used in the Cobb method and method of Nash and Moe are the vertebral endplates and pedicles respectively. Although these landmarks are considered to be less affected by congenital abnormalities than other landmarks,[37] all landmarks can be deformed by the accumulative forces involved in scoliosis (the Heuter-Volkmann principle). Additionally, anatomical variations can cause severe alterations in a curvature between the identified end-vertebrae without the Cobb angle being effected. This is because the Cobb measurement assumes that the vertebrae between the identified end vertebrae will form a perfect arc.[35] Additionally, physiological alterations in landmark orientation can occur. Beauchamp et al. have noted that the Cobb angle can change over the course of the day (diurnal variation).[38]

Assuming that the landmarks of interest are within normal limits with respect to their geometry, error in measurement is often created from the human being responsible for identifying and then marking the target landmark. Various influences have been suggested or shown to produce variability in how films are marked by examiners: the quality of the image,[39] the specific profession (training) of the examiner,[40] the choice made as to which vertebrae bound the scoliotic curve,[41] the type of device used to assess the resultant angle[41] and the thickness the examiner's pencil lead.[42] The cumulative effect of these errors have been described to be as high as 9.6° for intra-examiner errors and as high as 11.8° for inter-examiner error.[43] Similar magnitudes of error have been shown to exist in the method of Nash and Moe for the assessment of vertebral rotation. Ho et al.[44] found up to 11° of error in the amount of rotation for vertebrae classified as Grade O (no rotation).

Based on these sources of error, calculations can be made as to what magnitude of change in a Cobb angle is necessary before one can be certain of significant anatomical change. These values range from 10 degrees[39] to as high as 23 degrees.[43] This poor confidence in the significance of the Cobb method has profound ramifications as various treatment protocols can be mistakenly applied or withheld. Although measurements such as the Cobb angle provide a way of numerically assessing scoliosis, their potential for large magnitude measurement errors can render them no more effective than observational methods.

As with all methods used in scoliosis assessment, various alternatives, patches and fixes have been proposed for methods of plain film quantification. While some improvements do offer reduction of error (i.e. digitization of landmarks),[45] there is still an additional concern about measurement methods based on plain film analysis: two dimensional (2D) representations do not appropriately describe three dimensional phenomenon.[35,46] This disparity is the result of dispersion of the beam from its source. Therefore, only a small percentage of the primary beam that approaches the subject does so perpendicularly. As a result, most structures appearing on the film are in some way distorted and/or magnified. Depending on technical factors such as entry angle of the primary beam and source-subject/subject-film distances, the resultant magnification and distortion that occurs may be significant and introduce error in the process of landmark identification. This problem becomes substantially greater and increasingly apparent when the objects of interest are staggered from the point of beam generation. Objects located closer to the film will be affected differently than objects located further from the film.

A simple example is presented that describes these phenomenon as they relate to a uni-planar curve. If a beam of light is shone on such a curve, the resulting shadow will be distorted based on the object's distance from the primary beam. If that curve is now rotated as a single unit about its long axis and the beam origin and viewing perspective do not change, the projected angle of the curve appears to change despite the fact the curve has not physically changed. Similarly, the Cobb angle and other roentgenometric measurements are greatly influenced by the amount of rotation within the curvature. Therefore, as radiological studies are typically performed in the frontal and lateral planes, the vertebrae within a scoliotic curve are usually seen obliquely. As a result, the true angle of the curve is not apparent because of this oblique projection.[47] These problems of magnification, distortion and projection can add errors of over 29° (41%) in the Cobb method alone. [46]

Quantitative methods based on 3D image processing

Computed tomography and MRI

Computed tomography, or CT, is a process where 2D images are taken in three orthogonal planes (frontal, sagittal and transverse) then reconstructed by computer to create a three dimensional representation which can be manipulated by sophisticated computer graphics packages to be viewed in any orientation. Based on the parameters of the scan, the resulting 3D image is one that is very detailed with respect to spinal and vertebral morphology.[48,49] As a result, this procedure is used to assess curve shape, curve orientation and intravertebral geometry.[50]

The disadvantages of CT based methods are many.[49] Primarily, the method uses ionizing radiation and at best, requires dosages equivalent to those experienced in plain film analysis. Additionally, the time involved with creating a CT scan is considerable which makes the procedure liable to movement artifacts. CT scans are also performed while the subject is recumbent, therefore, the resulting portrayal of the spine is not weight-bearing, a feature considered to be clinically important. These problems, in addition to errors caused by inaccurate location of anatomical landmarks, can create errors of up to 30° for various vertebral rotations.[51] For these reasons, as well as an increased cost compared to plain film analysis, CT-based scoliosis analysis is typically limited to research investigations. Comparatively, magnetic resonance imaging techniques do not possess the risks associated with imaging techniques that employ ionizing radiation, but are equally limited to research roles as the modality is time consuming, costly and does not optimally portray bone.

Photogrammetry

Photogrammetry is the science of obtaining measurements from photographs. In scoliosis analysis, this method can be used with the 2D images created by plain film methods to "reconstruct" images of the spine which are three dimensional in nature. The basic principle of this method is that a point can be located in space if viewed from 2 different projections, given some information regarding distance.[52] This procedure was first employed for spinal visualization by using manual calculations, a very laborious endeavor.[33,53] The development of computer algorithms to perform the necessary calculations has since made this procedure much more practical[54] and of potential clinical use.

There are several methods of creating a three dimensional image from plain films. The orthogonal method requires two radiographs of the spine which have been taken at right angles two each other. This can be achieved by using two x-ray tubes placed perpendicularly to each other, by physically moving the x-ray tube around the patient or by rotating the subject 90° with respect to the x-ray tube.[55] Stereo-base imagining is another method where the first plain film is taken in the traditional AP or PA orientation and the second by moving the x-ray tube superiorly or inferiorly then angulating the tube so that the primary beam passes through the general location as it did on the AP or PA view. This approach has been advocated for use when physical or budgetary limitations prevent the orthogonal approach.[55] Using either method, an object housing radio-opaque objects at known distances is assessed by the procedure of choice to calibrate the system.[56] Digitization is then used to locate the same landmark in each of the two films (landmark pairs).[52] By comparing the landmark pair distances with those directly measured from the calibration object, the location of each object is triangulated and its point in space determined by direct linear transformation algorithm.[57] The resulting information can then be reconstructed and displayed from any desired angle as a three dimensional representation of the spine. Once the system has been calibrated, human subjects can be assessed in this manner.

Although photogrammetric methods offer several improvements over two dimensional measurements, photogrammetric methods still have significant sources of error which can limited their performance. Errors in locating the calibration objects can create errors of ± 0.1 mm in orthogonal methods versus errors of ± 1.0 mm when using stereogrammetry.[55] In an object such as the spine, precisely locating anatomical landmarks with irregular borders on two different views is many times more difficult than identifying regularly shaped calibration objects.[55,56] These types of errors are more common and can be greater in magnitude in stereophotogrammetry than in the orthogonal method. This is due to the greater amount of superimposition of structures and the greater distortion of the shape of structures in angulated views as compared to orthogonal views on the same plane. Recent work by Andre et al.[55] has determined the tube angulation and landmark pairings that make stereo methods approach orthogonal methods in terms of error, however, errors of up to 15.0 mm can still occur.

Compared to CT-based methods which provide very detailed three dimensional reconstructions, photogrammetric methods create minimal three dimensional representations of vertebrae which resemble linked polygons. Using various computer graphic techniques, these polygons can be manipulated and viewed in any orientation.[58] To approach the volume of reconstruction obtained by CT using a sterophotogrammetric method, it is not possible to digitize a larger number of landmarks because the majority of landmark pairs in any two views can not be properly identified due to distortion and superimposition.[52,56] Despite the incomplete nature of this method, photogrammetric methods give 3D representations that are low cost, low exposure, performed in weight bearing positions and utilize readily available equipment.

Currently, researchers are utilizing photogrammetry in the study of scoliosis. Using this method, one can rotate the scoliosis about the mid-line longitudinal axis and determine at what point the curve is at its greatest using a Cobb-type measurement. The plane of this position has historically been called the election plane,[47] but more recently, as the plane of maximal curvature.[59] This plane can then be referenced with respect to the frontal, sagittal and transverse planes. While the measurement of the curve still suffers from some of the errors previously identified with Cobb-type measures, the use of these photogrammetric methods avoids measuring the curve from the frontal plane which causes curve distortion.

Photogrammetric methods have been used in pre-post surgical studies and identified a significant movement of the maximal plane of deformation toward a "normal" axis. The curvature itself did show small but significant changes in rotation and Cobb angle (3D equivalent), but the largest changes were noted in the plane of maximal curvature.[59,60] By employing three dimension assessment methods, these new studies are describing what has been suspected for some time: traditional Cobb measurements do not properly describe the scoliosis and therefore lead to improper decisions regarding treatment application and/or efficacy.

Conclusion

While all methods of scoliosis quantification are problematic, direct measurement of scoliosis from two dimensional imaging methods is currently the "gold standard". Recent evidence suggests that these gold standard measurements of scoliosis can be highly inaccurate and may not be clinically valid. While lack of alternatives have perpetuated the use of these techniques in the past, recent methods of scoliosis quantification are now available (photogrammetric methods) which are thought to provide measures that are at least as reliable as traditional measures but have improved validity. Although evidence is lacking, these new procedures appear to be equal to plain film methods in terms of risk and cost, but are not yet widely utilized due to a combination of decreased awareness, lack of training and minor equipment requirements.

The benefits of photogrammetric methods of scoliosis quantification have not yet been completely defined. Clearly, studies need to be performed to 1) determine how to best measure a curve once it has been visualized three dimensionally and 2) determine the validity of the these measurements with respect to clinical, functional, cosmetic, and physiologic outcomes.

As these studies have not yet been performed, the use of these techniques for scoliosis assessment can not be equivocally advocated. Chiropractors and others who are involved in the management of scoliosis must be aware of these and similar developments so that their implementation is appropriate and timely.

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