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CASE SERIES

Evaluating the role of surface topography in the surveillance of scoliosis

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Abstract

Study design Literature review.

Objective To review the history, modern uses, limitations, and future direction of surface topography (ST) in surveillance of scoliosis.

Summary of background data Spinal deformities, including scoliosis, can be characterized using measurements such as the Cobb angle, lateral curvature, and vertebral rotation. The gold standard for diagnosis and surveillance of such deformities utilizes radiographic images. To minimize repeated radiation exposure, many systems have been developed utilizing ST. ST measures local deviations of a surface from a flat plane. Applying this concept to spinal deformities, ST can non-radiographically study the 3-dimensional shape of the back. One ST system, rasterstereography, projects parallel white light lines onto a patient's back and analyzes line distortion with a camera. While radiography has long been considered the primary diagnostic tool for scoliosis, rasterstereography may possess alternative or complementary benefits in monitoring scoliosis and other diseases.

Methods A comprehensive literature review was performed on the history, development, and validity of ST. The advantages and limitations of this technique were compared to those of radiography.

Results While the initial goal of ST, designing a system to accurately reproduce the Cobb angle, was not successful, research efforts over the last 40 years have attempted to improve this correlation. ST technologies, including rasterstereography and the Formetric ST System, currently play important roles in scoliosis surveillance, research, and minimizing radiation exposure in longitudinal care of patients. Such technologies are also useful as an adjunct to X-rays for monitoring disease progression, especially in Parkinson's disease.

Conclusion Despite its limitations, ST has proven useful across multiple fields of medicine. It is a safe and cost-effective tool for long-term surveillance of scoliosis and early detection of progressive disease. With technological improvements, the Formetric System will become a critical alternative in dynamic spinal motion and gait analysis.

Level of Evidence N/A.

Keywords Scoliosis · Radiography · Rasterstereography · Surface topography · Spinal deformity

Introduction

Scoliosis is a common, mostly idiopathic, lateral curvature of the spine. Such structural deformity can be assessed using radiographic and topographical measurements. Anterior–posterior radiography has long been considered the gold standard for diagnosis of scoliosis, as it utilizes X-rays to directly image the internal morphology of the spine [1]. Objective measurements, such as the Cobb angle and vertebral rotation, can be gathered from radiographic images and used to characterize spinal deformities [1, 2]. The Cobb angle, defined as the angle formed from intersecting lines drawn perpendicular to the vertebral endplates above and below the scoliosis curve, is currently the primary diagnostic measurement for scoliosis [2, 3].

With widespread use of repeated full-column radiographs for diagnosis and surveillance of scoliosis, especially among adolescents, various non-radiographic systems have been developed utilizing surface topography (ST). ST analyzes

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the small local deviations of a surface from a perfectly flat plane. It is currently utilized in various programs, including Google Earth to create 3-dimensional representations of the Earth. ST can also be applied to orthopedic studies through its analysis of the 3-dimensional shape of the surface of the back. One ST method, rasterstereography, projects parallel white light lines (raster lines) onto a patient's back. The 3-dimensional shape of the back distorts these lines, producing a curved light pattern detected by a camera. Assigning convex or concave areas allows anatomical landmarks and fixed points to be immediately captured, calculating a 3-dimensional model of the spine. This technique was developed as an alternative to radiography, with the purpose of reducing patient lifetime exposure to ionizing radiation [4].

ST technologies were created to design a system that could accurately reproduce the Cobb angle. However, research has shown that diagnostic measurements between radiography and ST do not correlate reliably [5]. Research efforts over the past 40 years have attempted to improve the correlation, with limited success. Although ST has been shown to have narrow diagnostic relevance, it is used today as an adjunct to X-ray for monitoring disease progression [6]. In addition, it has the potential to play a role in scoliosis surveillance, research, and minimizing radiation exposure in longitudinal care of patients. This paper will review the history, modern uses, limitations, and future direction of ST.

History and development

There is a well-studied, dose–response relationship between exposure to ionizing radiation and the development of malignancy [7]. Many clinicians treating scoliosis first encounter their patients at a young age. Throughout the course of the patient's care, many undergo repeated X-rays and, therefore, will be exposed to an above average radiation burden [2, 4]. Such high exposure is problematic as growing tissues and organs in pediatric patients are particularly susceptible to the oncogenic effects of radiation [8]. Additionally, malignancies associated with radiation exposure develop over decades. Pediatric patients undergoing repeated X-rays have a higher lifetime risk of malignancy compared to adults, as they possess more years in which malignancy may manifest [8]. Recent research has shown that adolescent females with scoliosis had 1.82 increased incidence of breast cancer when exposed to serial X-rays from a young age [9]. To mitigate the risks posed by radiation exposure, clinicians recognized the need for alternative methods in describing truncal deformities.

The scoliometer was one of the first attempts at utilizing ST measurements to characterize the spine. It was used to calculate truncal rotation in scoliosis patients, defined as the angle between the horizontal plane and the plane of the posterior trunk [10]. The magnitude of the angle was directly related to the severity of the scoliosis and the deformity of the rib cage. Scoliometry was cost-effective and simple to perform, but due to its measurement of truncal rotation rather than magnitude of coronal curve, correlation with Cobb angle was not strong ($r = 0.3$–0.5) [11, 12]. While this prevented it from becoming a first-line diagnostic instrument, the scoliometer is now used together with the forward bending position (Adam's test) as a noninvasive scoliosis screening tool. This test is useful in identifying children at risk of idiopathic scoliosis and, thus, determining which patients need radiographic follow-up [12]. The shortcomings of scoliometry encouraged research into more advanced tools for describing back-surface anatomy.

Moiré topography was the next step in ST analysis. The technique was developed in the 1970s and was used by medical researchers in the mid-1980s for non-radiographic detection of scoliosis [6]. Early systems projected a moiré grid onto a subject's back and captured a photograph [13] (Fig. 1). The photograph was digitized and analyzed by computer software to generate a topographical reconstruction. Mathematical models reproduced the contour of the back by studying the distortion of the parallel grid along its surface [13]. The analysis was slow and burdensome, preventing efficient use by those in clinical practice. However, as computer capability improved and enhancements were made, the analytical power of this technology became apparent and was referred to as rasterstereography [6].

Subsequent efforts in utilizing ST focused on the mathematical reproduction of the radiographic Cobb angle. Two early optical techniques, Integrated Shape Imaging System (ISIS) and Quantec Spinal Image System (QSIS), pioneered this approach and used advanced computer models to estimate the Cobb angle from ST data [14]. These structured light systems utilized a standard television camera and projector, mounted in a fixed relationship to allow movement around a horizontal axis. The projector creates a horizontal plane of light, with which the camera rotates to capture 50–100 frames (Fig. 2). Such rotation contrasted conventional photogrammetric methods that utilized a stationary camera [15]. These features increased the aspect ratio of the photograph and decreased nonlinear distortion of the picture [15]. Despite these advances, correlations between lateral asymmetry and Cobb angle from these systems ($r = 0.84$) tended to be within 10° of the radiographic measurements. They were thus insufficient for diagnostic use, as the measurement of Cobb angle itself possesses an interrater variability of 5° to 10° [16, 17].

Within the past two decades, the Formetric ST System has emerged as one of the more advanced surface topographical technologies. This system combined rasterstereography, a method of ST analysis, with biomechanical modeling to generate measurements of the body surface. It was first developed at the University of Muenster and commercialized by the DIERS Company (Schlangenbad, Germany) in the mid-1990s using a sophisticated evaluation of truncal ST. In Muenster, Drerup and Hierholzer developed a complex mathematical model that correlated topographical scans with thousands of reference spinal radiographs [1, 18, 19]. The data were used to produce 3-dimensional reconstructions of the spinal columns, improving upon two-dimensional radiographic representations. Validation of this model was done by the DIERS Company in partnership with the University of Muenster and several other international universities [20].

One of the functions of the ST System that set it apart from other technologies was its ability to accurately locate human anatomical landmarks, including the vertebrae prominens and posterior superior iliac spines (PSIS) [21–23]. Subsequent research demonstrated that the system could locate these landmarks more accurately than an experienced clinician [24]. The landmarks are essential to modern topographical analysis because they establish a patient-centric, fixed-coordinate system. The vertebrae prominens and the midpoint between the two PSIS anchor the system (Fig. 3). Each coordinate graph is individualized to the patient and moves as the patient does. Data are measured in relation to the anchor points and averaged across several consecutive images. This protects the analysis from minor changes in patient position relative to the equipment [22, 23].

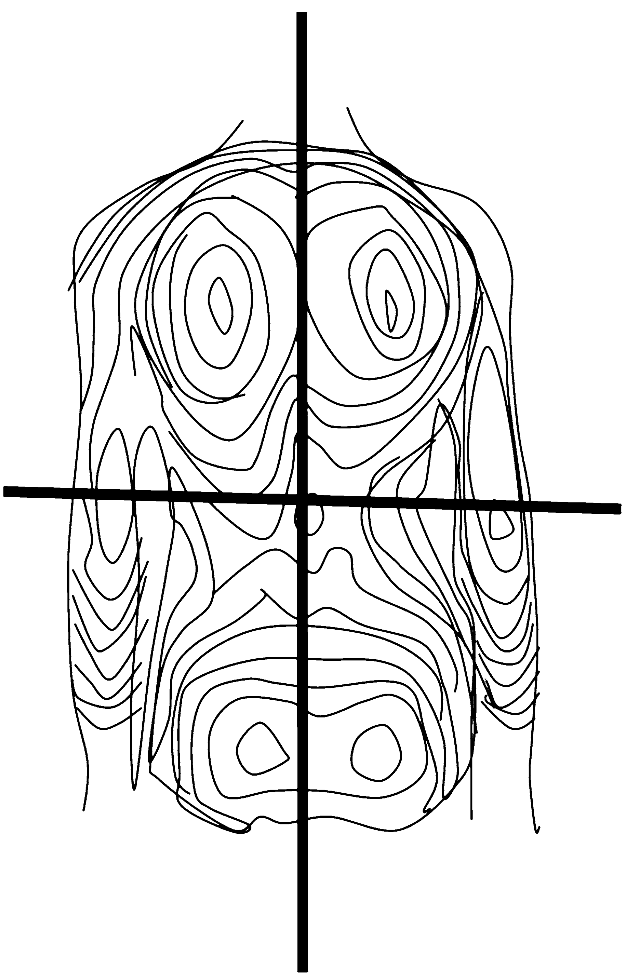

Fig. 1 Radiation-free projection of moiré grid onto the surface of patient's back. Pattern of alternating clear and dark fringes is utilized for further analysis

Independent evaluation of the ST System began after it was introduced into European and US markets. Research focused on the instrument's ability to calculate spinal measurements used in the evaluation of scoliosis and instrument precision. Initial precision studies used ST to record 30 consecutive topographical measurements on volunteer patients. The system showed strong test–retest reproducibility, with Cronbach's alpha of 0.996 for angular measurements of scoliosis [1]. The standard deviation for the same-day repeated scans was 3.4°, similar to the variance found when two clinicians interpreted the same radiograph [1]. Further studies using different examiners found a high intrarater reliability (Cronbach's alpha from 0.921 to 0.992) and interrater reliability (Cronbach's alpha 0.979) [25].

Limitations and concerns

One concern regarding ST was that it was not accurate across all body habitus. As the technology relies upon identification of the spinous process contour, it was unclear whether increased subcutaneous tissue in overweight patients would distort this measurement. However, in a study concerning the effect of BMI between 16 and 29 in female patients, ST measurements were reliable. While the study found ST measurements to be most accurate with lower BMI, the standard deviation of the spinal measurements was only 4.6° at the maximum measured BMI of 29 [26]. Studies have yet to focus on topographical accuracy in obese individuals with BMI greater than 30.

Another question regarding the use of ST was whether it could accurately reproduce standard radiographic measurements, including the Cobb angle. In a multicenter study, Knott et al. attempted to address this question. Researchers compared surface topographical with conventional radiologic techniques in 193 patients with adolescent idiopathic scoliosis (AIS). The study focused on measurement of the Cobb angle at different spinal segments. The strongest correlation with radiographic measurements was in the thoracic spine ($r = 0.7$), and moderate correlation was found in the lumbar spine ($r = 0.5$) [5]. The average Cobb angle variation from radiograph was 5.8° in the thoracic region and 8.8° in the lumbar region. Although the study showed that ST has made improvements in analysis of spinal curvature, it

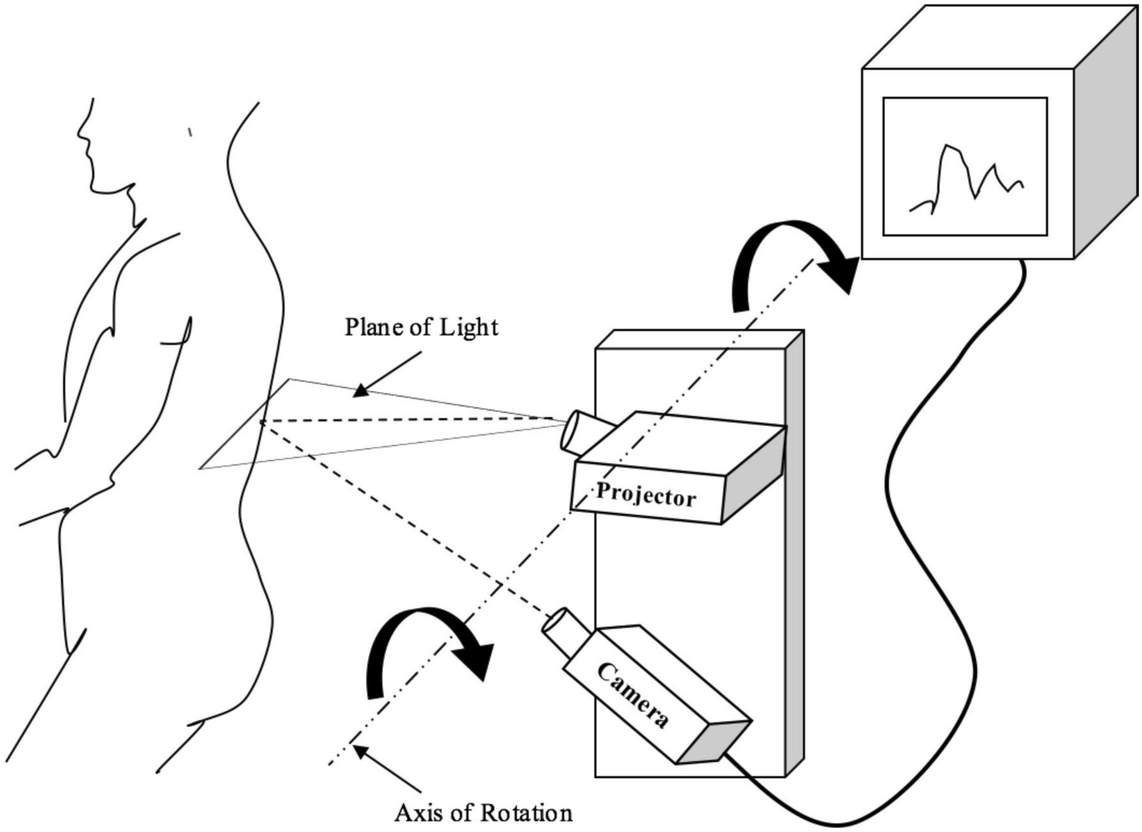

Fig. 2 Integrated Shape Imaging System (ISIS) mechanism, utilizing a mounted projector and rotating television camera to measure surface topography of the human back

ultimately concluded that the technology did not meet the threshold accuracy required for it to be useful as a primary diagnostic tool. The system instead would be utilized as a reproducible means of detecting change in deformation following initial radiographs, reducing the need for serial radiographs [5].

Many theories attempt to explain the inability of ST technology to reliably calculate the Cobb angle. The discrepancy has partly been attributed to small variations that exist within the spinal surface rotation curve. Researchers argue that these variations are miniscule enough that they do not affect gross measurement of lateral deviation and vertebral rotation. However, they note an important difference between radiographic and rasterstereographic Cobb angle calculation. The Cobb angle is measured radiographically from the vertebral endplate, while rasterstereography measures the Cobb angle from the surface contour of the spinous processes. Therefore, when calculating the Cobb angle from rasterstereographic data, the spinous process acts to amplify each variation within the spinal curve [4–6]. In other words, the Cobb angle measured from the spinous process is magnified compared to the measurement from the vertebral endplate. Since determination of the Cobb angle is the basis for clinical treatment of scoliosis, ST has not proven to be an effective diagnostic replacement for X-rays. However, clinicians have recognized that there are other applications for the technology.

Modern uses

The importance of reducing adolescent exposure to ionizing radiation cannot be understated. As the Cobb angle is best calculated from X-rays, various advancements have been made to simultaneously limit radiation exposure and maintain imaging quality. Such advancements include a slot-scanning X-ray technique by the EOS™ imaging system, with the use of a micro-dose protocol. This protocol reduced the entrance skin dose by 5.9–27.0 times and the organ dose by 16–34 times as compared to standard digital radiography on patients with AIS [27]. In addition, posteroanterior EOS radiographs had an 8 times lower radiation breast dose and

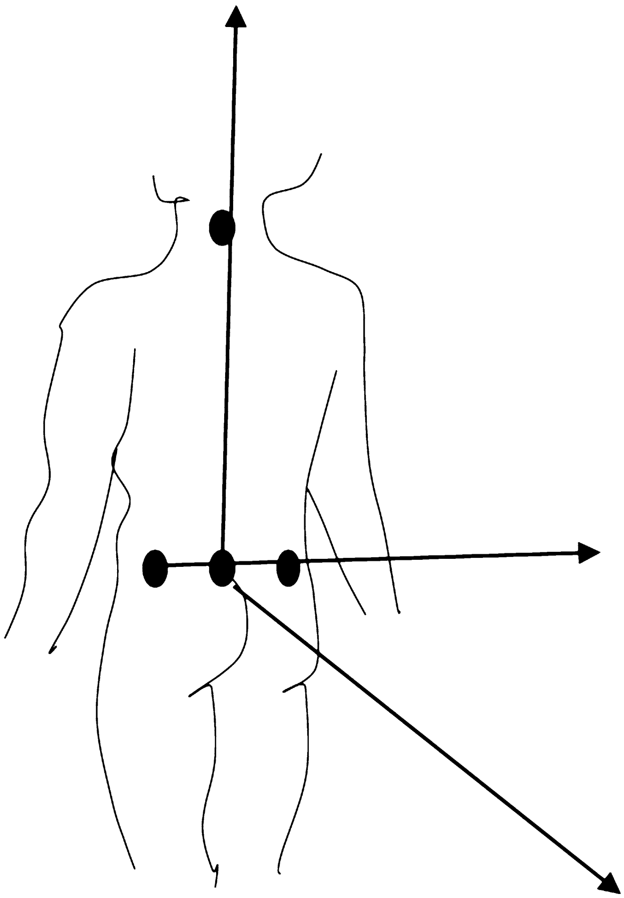

Fig. 3 The vertebrae prominens and midpoint of two PSIS as anatomical landmarks for fixed-coordinate system on back-surface

4 times lower radiation thyroid dose than anteroposterior EOS radiographs [28]. Combining the micro-dose protocol with a posteroanterior film significantly decreases adolescent radiation exposure, while maintaining the gold standard of diagnosing scoliosis.

While the EOS system has significantly reduced the radiation exposure for patients with AIS, the system is not without limitations. Such limitations include the need for a well-trained operator, a time-intensive reconstruction of the bone segment and poor image quality if the patient cannot stand or sit steadily during the imaging process [29]. The system thus has limited application to patients with a neuromuscular or neurologic disorder. In addition, despite its reduction in radiation exposure compared to conventional digital radiography, the EOS system still possesses a carcinogenic risk from repeated radiographic use, especially to the adolescent population. In contrast, ST is attempting to establish itself as a radiation-free and inexpensive tool for long-term surveillance of spinal deformities [5]. This technology can be used repeatedly during follow-up visits without concerns of radiation exposure [6]. In addition, it allows rapid static and dynamic measurements of the spine. During each scan, ST collects 12 images of the posterior trunk over the course of 6 s. A 3-dimensional model of the back and spine is then constructed. The sensitivity of the system allows clinicians to recognize and respond to postural changes early on. Serial use of the system may paint a clearer picture of patient progression and response to treatment over time. ST captures patients in their normal, habitual posture, avoiding some of the unnatural postural changes induced by positioning the patient in front of the X-ray machine [6]. Furthermore, researchers have demonstrated that ST can be used in patients with scoliosis after anterior and posterior correction and fusion [30, 31]. However, prior to utilization, proper technician training is essential. A member of the DIERS Formetric team will train a technician over the course of half a day. The representative should return periodically to ensure proper training and implementation.

In addition to its use in long-term surveillance of patients, ST has been useful in assessing the vertebral rotation (VR) of scoliosis. Mangone et al. compared the use of X-ray and ST in the evaluation of VR in AIS patients [32]. The study examined VR correlation in the whole sample ($N=25$), in thoracic and lumbar spinal segments considered separately, and in subgroups of patients with Cobb angle measurement greater or less than 30°. The study determined a significant VR correlation between radiographic and rasterstereographic analysis in all groups. The research confirmed the utility of using noninvasive methods for the assessment of spinal deformity in AIS patients [32]. However, studies with larger sample sizes need to be performed.

The use of ST is not limited to patients with AIS. Khallaf and Fayed utilized ST to examine the onset of postural changes in patients with idiopathic Parkinson's disease [33]. Postural abnormalities are common in such patients, affecting gait, standing, and truncal balance. Khallaf and Fayed demonstrated that these postural changes begin to occur early in disease progression, independent of duration and severity of illness, but are not recognized until they interfere with daily life [33]. ST was ideal for this study because it had adequate sensitivity to identify early variations in patient posture and did not require exposure to radiation. This study suggests that ST is a potentially useful tool for management of patients with Parkinson's disease.

ST is ubiquitous in spinal postural research. Studies have utilized the cost-effective system for a wide array of research topics, including optimizing pelvic obliquity treatment, evaluating lumbar back pain, and determining changes of spinal posture due to thoracic/lumbar spine fractures [34–38]. Grivas et al. utilized ST to assess the effect of mild, below 2 cm, limb length inequality (LLI) on pelvic imbalance, spinal posture, and Cobb angle in children. Consistent with prior studies utilizing radiographic methods, there was no correlation between mild LLI and Cobb angle. However, LLI had a significant influence on pelvic imbalance and spinal posture. As a result, correction with shoe elevations was deemed necessary for mild LLI. The study also recommended continual follow-up with the use of ST imaging until patient maturation [39].

Other uses of ST include those associated with pregnancy. ST is safe to use in pregnancy and has assisted studying lower back pain and postural changes in such women [40]. Other studies have used ST in assessing spinal balance in patients with spinal cord injury and for determining postural alignment in patients that have suffered cerebrovascular accidents [41, 42]. Furthermore, other clinical tests including the Adam's test and Matthias posture test can be quantified with this technology [43, 44].

Future direction

Betsch et al. suggest that the next phase of ST analysis will utilize the Formetric ST System under dynamic conditions [45, 46]. The system can measure at a rate of 50 frames per second, allowing clinicians to visualize the 3-dimensional shape of a patient's spine during the gait cycle [46]. This type of analysis is integral to understanding the full scope of truncal deformities, as some pathologies only become evident during movement [47]. Current gait analysis technology is costly and time-consuming. As a radiation-free system, application of ST to gait analysis could provide useful and cost-effective alternatives [47]. Initial studies into this function indicate that the present ST technology is precise and produces error ranges comparable to the current gold standard in dynamic spinal motion analysis. It can reliably be used for evaluating segmental spinal motion and spinal curvatures [48]. In addition, the ST system can be easily assembled and disassembled in a standard office space, approximately 150 square feet. It is thus practical for clinical use. Aside from its clinical application, ST can be used for all orthopedic research, including gait analysis. Utilizing this radiation-free system will allow more efficient and timely prospective study designs.

Conclusion

Despite its limitations, the use of ST among various imaging modalities has the potential to be relevant in scoliosis and possibly other fields of medicine. As a noninvasive, radiation-free technique, ST can be utilized in the surveillance of scoliosis and has broad applications in research. Technological improvements in surface topographical systems will continue to support its role in describing the dynamic biomechanics of the human body and enhancing clinical practice.

Key points

- The Cobb angle, the primary diagnostic measurement for scoliosis, is obtained through radiographic imaging and, therefore, poses an increased risk of malignancy to the patient from high radiation exposure.
- To minimize repeated exposure to ionizing radiation, many non-radiographic systems, such as rasterstereography, have been developed that utilize surface topography of the back to create a 3-dimensional model of the spine.
- The Formetric Surface Topography System has become one of the main rasterstereographic technologies over the last two decades, with its ability to precisely locate anatomical landmarks and minimize for subtle changes in patient position relative to the machine.
- While surface topographical methods could not accurately reproduce the Cobb angle obtained through radiography, research efforts and technological improvements have allowed surface topography to play an important role in long-term scoliosis surveillance, early detection of progressive diseases, research, and in minimizing radiation exposure in the longitudinal care of patients.

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Compliance with ethical standards

Ethical approval The device(s)/drug(s) is/are FDA-approved or approved by corresponding national agency for this indication.

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