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Computer Modeling

Simulation of a Bead Placement Protocol for Follow-up of Thoracic Spinal Fusion Using Radiostereometric Analysis

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Abstract

Study Design: Computer simulation to detect intervertebral motion enabling future follow-up of spinal fusions performed on patients with multilevel thoracic scoliosis.

Objectives: To propose a method using computer simulation to evaluate a radiostereometric analysis (RSA) marker placement protocol for visibility and redundancy and validate the performance of the developed RSA system in detecting intervertebral motion.

Summary of Background Data: Radiostereometric analysis is a stereo x-ray technique in which clusters of tantalum markers are implanted to label well-defined landmarks and measure the relative motion between rigid bodies.

Methods: A model of the spine with the instrumentation and the RSA markers was developed. The vertebrae were aligned to mimic multilevel thoracic scoliosis after correction. The researchers performed virtual segment motion to validate the performance of the developed system. X-ray images were simulated and RSA was used to evaluate the proposed marker placement protocol and detect virtual motion. The authors performed a physical phantom study to evaluate marker visibility.

Results: All markers were located and matched between simulations and the condition numbers were well below the recommended value of 100. Based on computer simulation, average translational accuracy was 0.14, 0.01, and 0.24 mm along the *x*, *y*, and *z* axes, respectively, and average rotational accuracy was 0.23°, 0.12°, and 0.11° about the *x*, *y*, and *z* axes, respectively. The translational and rotational precision of the simulated RSA system was generally high. The physical phantom study agreed with the computer simulation and validated marker visibility.

Conclusions: Computer simulation is a powerful tool that can be used to facilitate the development and refinement of an RSA system before its application in patients, particularly when the anatomy involved is complex. The proposed marker placement protocol yielded translational and rotational accuracy below the limits of clinical significance, which enables future follow-up of multilevel thoracic scoliosis with Lenke classification 1AN.

Keywords: Radiostereometric analysis; Computer simulation; Intervertebral motion; Multilevel fusion; Thoracic scoliosis

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Introduction

The surgical treatment of adolescent idiopathic scoliosis (AIS) aims to obtain a solid bony fusion and thereby prevent further curve progression. A secondary goal is to reduce the curve magnitude and achieve a well-balanced, stable spine [1]. Current instrumentation systems are based on segmental stabilization; however, debate continues in the pediatric spine literature over which technique is best suited for the treatment of AIS to achieve superior curve correction and absolute spinal fusion [2-6].

A main challenge that spine surgeons face is the ability to determine the success of spinal fusion while minimizing radiation to patients. The measurement of fusion success involves assessing both the structural stability and functional integrity of the fusion [7]. The reference standard for measuring the success of spinal fusion, from both the structural and functional perspectives, is direct surgical exploration [8-10]. However, this method is seldom used because it is highly invasive and costly, and provides no temporal information about the stability of the fusion [11,12]. Beyond this approach, all available imaging modalities including conventional radiography, computed tomography, and magnetic resonance imaging are limited in their ability to provide clinically relevant measurements of fusion success.

Radiostereometric analysis (RSA) is a stereo X-ray technique in which clusters of tantalum beads are implanted to label well-defined landmarks and measure the relative motion between rigid bodies. Radiostereometric analysis can be used to detect motion between intervertebral segments and even monitor changes in this motion between follow-up exams. Axelsson and Karlsson [13] used RSA to assess intervertebral mobility in 18 patients experiencing progressive degeneration of the lumbar segments. Their study revealed minute yet distinct motion between the intervertebral segments corresponding to intervertebral mobility changes throughout the degeneration process. Furthermore, Pape et al. [12] investigated the use of RSA for assessing intervertebral mobility after lumbosacral fusions. Radiostereometric analysis was used to assess postoperative stability over time (every 3 months) and 4 weeks after instrumentation removal, which was undertaken after solid fusion. According to RSA data, solid fusion was assumed when translation between L5 and S1 vertebral segments did not exceed 0.3, 0.5, and 0.7 mm along the transverse, vertical, and sagittal axes, respectively. Their direct surgical exploration correlated with the RSA data and confirmed the adequacy of RSA as an in vivo predictor of lumbosacral fusions. Johnsson et al. [14] also used RSA to study intervertebral mobility after posterolateral lumbosacral fusion. Their study aimed to determine the timetable for intervertebral stabilization in 11 patients. Using RSA, small decreases in intervertebral mobility ranging from 12 to 0.4 mm were detected over time until the occurrence of rigid spinal fusion, which varied between 3 months and 1 year.

Although there are few studies [12-20] in the literature in which RSA has been used to evaluate spinal fusion, the results of these studies point to the suitability of RSA as an effective tool for evaluating fusion success. To the authors' knowledge, no published studies have evaluated the use of RSA in patients with thoracic scoliosis who have been treated with multilevel fusion and segmental instrumentation. The aim of this study was to propose a method via which a computer simulation is used to 1) evaluate an RSA marker placement protocol for visibility and redundancy and 2) validate the performance of the developed RSA system in detecting motion between intervertebral segments T4 to L1, enabling future follow-up of the surgical fusion of a right main thoracic AIS curvature with Lenke classification 1AN [21].

Materials and Methods

Because posterior spinal fusion of thoracic AIS involves relatively complex spine anatomy and 3-dimensional rotation of the vertebrae, it can be difficult to distinguish markers inserted into adjacent vertebrae. Markers were thus only inserted into the T4, T8, and L1 vertebral segments and the success of spinal fusion was measured by detecting motion among 3 segments chosen to represent the cranial, apical, and caudal vertebrae of the AIS curvature.

Computer-aided design model development

The researchers used Solid Edge (ST2, Siemens PLM Software, Plano, TX) to draw the 3 vertebral segments [22]. Quantitative 3-dimensional morphometrics of human thoracolumbar vertebrae were used to adjust the dimensions appropriately to mimic the anatomy of the human spine [23,24]. The T4, T8, and L1 vertebral segments were positioned to simulate the curvature after the correction of right main thoracic AIS, with 20° residual scoliosis and 20° physiological thoracic kyphosis (Table 1). Computer-aided design (CAD) of pedicle screws, rods, and cross-links from the DePuy 5.5-mm Expedium titanium system (DePuy Spine, Raynham, MA) were incorporated into the model (Table 2). Seven spheres 1 mm in diameter, representing tantalum markers, were inserted in different locations across the vertebral segments as per the proposed marker placement protocol (Fig. 1, Table 3). A virtual calibration box for RSA imaging was developed to mimic the Halifax Medis box (Halifax Carbon Box 18, Medis Specials, Leiden, The Netherlands). Subsequently, the developed vertebral segments with the markers and AIS instrumentation were virtually positioned with respect to the calibration box to mimic patients lying prone on the X-ray table during an RSA exam (Fig. 2).

Validation study using simulated segment motion

The first goal of the validation study was to assess the performance of the developed RSA system in detecting intervertebral motion with translational and rotational