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Effect of Distraction Force on Growth and Biomechanics of the Spine: A Finite Element Study on Normal Juvenile Spine With Dual Growth Rod Instrumentation

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Abstract

Background: Growth rods are used to limit the progression of scoliosis without restraining the opportunity for the spine to grow. The growth is sustained by consecutive distraction at intervals of 6 months. The optimal distraction force for a scoliotic patient is not defined adequately and rod breakage, screw loosening, stimulation of growth and altered sagittal contour has been observed.

Hypothesis: The hypothesis of this study is that for every patient with dual growth rods treatment there exists a distraction force that will sustain the growth of that patient's spine equal to normal growth with minimum changes in sagittal contours, results in lower von Mises stresses on the rods and minimum force at the pedicle screw-bone interface at 6 months.

Objective: In this finite element study, we undertook an objective to identify the effect of magnitude of distraction forces on the T1-S1 growth, maximum von Mises stresses on the rods, sagittal contours, and the load at the pedicle screw-bone interface.

Results: An optimal distraction force exists for which the growth is sustained with minimum stress on the rod, lower loads at screw-bone interface and unaltered sagittal contours. Another observation was that higher distraction forces (in the given range) didn't produce stresses on rod or load on screw that could result in failure of the implant.

Conclusion: Restoration of sagittal contour along with height restoration could guide the clinical practice, for the given range of distraction force.

Keywords: Juvenile scoliosis; Growth rods; Rod fracture; Finite element study; Distraction

Introduction

Distraction-based dual growth rods are the most commonly used growth-friendly surgical instrumentation [1,2]. Growth rods are used to limit the progression of scoliosis without restraining the opportunity for the spine to grow. The growth is sustained by consecutive lengthening surgeries at intervals of 6 months [3]. During such lengthening surgeries, the proximal and distal rods at each side are distracted apart [4]. Distraction has a significant role in final growth achieved at the end of 6 months, by virtue of the Hueter−Volkmann principle. Theoretically, it states that epiphyseal growth is affected by pressure applied at the growth plate; growth is inhibited by increased pressure, whereas a decrease in pressure accelerates growth. In theory, distraction leads to a decrease in pressure on the growth plates and helps sustain growth that otherwise would be lost [5,6].

Despite the many advantages of this system, there have been many instances of failure [7]. Rod fractures occur in 15% of patients treated with growing rods [3,8-10]. Although pedicle screws provide better anchorage, screw loosening occurs [11,12]. Some researchers also believe that the distraction forces applied are so high that they are stimulating growth rather than sustaining it [13,14]. Suboptimal

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distraction could also lead to poor sagittal contours in juvenile patients [15]. Therefore, there is a need to optimize the distraction force for sustained growth of the spine, along with an unaltered final sagittal contour, lower stresses on the rods, and minimal loads at the screw–bone interface.

The current authors hypothesized that for every patient with dual growth rod treatment, a distraction force exists that will sustain the growth of that patient's spine equal to normal growth. They also hypothesized that this optimal distraction force produces a minimum change in sagittal contours and results in lower von Mises stresses on the rods and minimum force at the pedicle screw–bone interface at 6 months. Thus, the objective of this study was to identify the effect of the magnitude of distraction forces on T1–S1 growth, maximum von Mises stresses on the rods, sagittal contours, and the load at the pedicle screw–bone interface using growth modulation incorporated within the finite element model of the spine. In this study, the approach used the finite element (FE) model of a normal juvenile spine.

Materials and Methods

An FE model of T1–S1 juvenile ligamentous spine (9 years of age, weighing 22 kg) was used in this study. The model was produced by personalizing the geometry of a previously validated adult spine model [16-19] to computed tomography data of a 9-year-old normal juvenile spine (Fig. 1). The material properties for the juvenile model were taken from the literature (Table 1) [20,21]. The authors then compared the model output with the only kinematic data (at 0.5 Nm) available in the literature for validation (Table 2). The validation was done with 4 lumbar motion segments and the moments used were 0.5 Nm for comparison with the published literature data [21-23].

Fig. 1. Dual growth rod instrumented juvenile spine (T1–S1) model (bottom) and intact juvenile spine (T1–S1) model (top).

Viscoelastic effects were included in the model to account for stress relaxation in soft tissues that may lead to a decrease in effective distraction force immediately after surgery (Table 3) [24,25]. Follower load was applied as reported by Schultz et al. [26] (ie, the spine was loaded with 14% body weight at T1 with a 2.6% body weight increase between succeeding vertebrae). Boundary conditions included restraining of the inferior surface of S1 vertebra at all degrees of freedom [27].

Vertebral growth plates consisted of superior and inferior epiphyseal plates. These were modeled near the 2 ends of each vertebra using isotropic and elastic hexahedral elements (Table 1). The pressure change was sensed at the growth plate, whereas new bone was added to the bone layers adjacent to it [27]. Growth was simulated based on the Hueter–Volkmann principle of growth modulation, expressed in the empirical equation:

$$G=G''[1+\beta(\sigma-\sigma'')]$$

where G is the actual growth strain, G'' is the mean baseline growth strain (at a given age), σ is actual compressive stress on the growth plate (in MPa), σ'' is the mean baseline stress on the growth plate for the intact spine (in MPa), and β is equal to 1.5 MPa^{-1} for vertebrae. For the intact model, G is equal to G''. G'' is equal to 0.035 per 6 months for a 9-year-old child spine, as per the published literature [28,29].

Integration of this growth modulation into the FE model was done by means of thermal expansion, converting the growth strains (calculated from above equation for each element) into thermal loads and applying those across the nodes [30].

All models consisted of 3 main steps of simulation:

Step 1

Eight pedicle screws and 4 rods (2 distal and 2 proximal) were implanted in the intact spine model. Four pedicle screws were anchored bilaterally at the pedicles of the T3

Table 1
Material properties used in the model for bone, ligament, intervertebral disc, and instrumentation.

Component	Element formulation	Modulus (MPa)/Poisson's ratio
Cortical bone	Isotropic, elastic hex elements (C3D8)	75/0.29 [20-23]
Cancellous bone	Isotropic, elastic hex elements (C3D8)	75/0.29 [20-23]
Growth plate	Isotropic, elastic hex elements (C3D8)	25/0.4 [21]
Posterior bone	Isotropic, elastic hex elements (C3D8)	200/0.25 [20-23]
Nucleus	Isotropic, elastic hex elements (C3D8H)	1/0.4999 [20-23]
Annulus (ground)	Neo-Hookean, hex elements (C3D8)	C10 = 0.348, D1 = 0.3 [16]
Annulus (fiber)	Rebar	357–550 [16]
Apophyseal joints	Nonlinear soft contact, GAPPUNI elements	12,000 [16]
Ligaments	Tension-only, truss elements (T3D2)	90% of adult ligament values [16,21]
Ti pedicle screws	Isotropic, elastic hex elements (C3D8)	115,000/0.3
Ti growth rods	Isotropic, elastic hex elements (C3D8), 4.5-mm diameter	115,000/0.3