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A biomechanical model for the idiopathic scoliosis using robotic traction devices

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Abstract. The mathematical modeling of idiopathic scoliosis has been studied throughout the years. The models presented on those papers are based on the orthotic stabilization of the idiopathic scoliosis, which are based on a transverse force being applied to the human spine on a continuous form. When considering robotic traction devices, the existent models cannot be used, as the type of forces applied are no longer transverse nor applied in a continuous manner. In robotic devices, vertical traction is applied and in addition, parameters such as magnitude, direction and angle of the force applied are required and essential, if the best therapy plan is to be administered. In this study, we propose a mathematical model to the idiopathic scoliosis, using robotic traction devices, and with the parameters obtained from the mathematical modeling, set up a case-by-case individualized therapy plan, for each patient. To the best of our knowledge, modeling involving these assumptions was never investigated before, neither was the usage of modeling to establish viable and effective bounds for all the possible parameters in a robotic traction device.

1. Introduction
Biomechanical models of the human spine, including idiopathic scoliosis, have been studied by several authors such as [1, 2] or even more recently in [6, 7]. In the classic [9], the portion of the human spine involved in a scoliotic curve is modeled as a uniform flexible column of homogeneous isotropic material, creating a curved beam column as mechanical analog. This proposed model failed to include the interaction between the human spine and the spinal musculature and other supporting structures. This interaction was later included in [3]. By introducing the flexural rigidity (or bending stiffness) factor (EI), the author shows that the behavior of the articulated human spine could be simulated by a continuous spine model. In [8] a spine-orthosis model is presented. This two-dimensional model describes the interaction of the spine with the orthotic stabilization device and is viewed in the frontal pane. Throughout the paper the authors establish the mathematical model comprised by a differential equation and assumptions on the boundary conditions. However the mathematical model used cannot explain or cover the forces involved in a robotic spinal traction device, such as the Antalgic Trak Technology. This type of devices have very specific features and characteristics that must be incorporated in the model, or read from the model as a specific output in order for the therapy to be as successful as possible. The methods used throughout this paper rely on mathematical modeling of the forces involved in robotic spinal traction devices, through the use of differential equations. To model such devices a
differential equation, along with the appropriate boundary conditions are presented. Analytical methods are used to obtain the solution and an analytical approach on the relation between the parameters is also presented. To better illustrate this relation, an individual test case is presented, where all the parameters, such as angle, force and point of incidence are presented. To the best of the authors knowledge, no existing model incorporates all of these features.

2. The spine-orthosis model

The spine orthosis model presented in [8] is based on the assumption that the portion of the human spine involved in a scoliotic curve is assumed to be biomechanically analogous to an initially curved beam-column, as shown in figure 1

![Figure 1. A biomechanical model of the spine orthosis-model](image)

One can notice the inclusion in this model of $Q$, which represents a distributed lateral load. This is introduced to simulate, in the same general solution, the stabilizing transverse load of the orthotic device used. This model is viewed in the frontal pane, hence the total lateral displacement, $y(x)$, is expressed as the sum of the initial lateral displacement, $y_0(x)$ and the lateral displacement due to axial and transverse loads, $y_1(x)$. Therefore,

$$y(x) = y_0(x) + y_1(x)$$  \hspace{1cm} (1)

The initial lateral displacement, $y_0(x)$, is assumed to be calculated by a curve-fitting technique based on an anteroposterior radiography, for each individual patient. As per $y_1(x)$, it is given by the solution of the differential equation

$$EI \frac{d^4 y_1}{dx^4} + P \frac{d^2 y_1}{dx^2} = Q(x) - P \frac{d^2 y_0}{dx^2}, \hspace{0.5cm} x \in \left[-\frac{L}{2}, \frac{L}{2}\right]$$

where $EI$ is the flexural rigidity or bending stiffness of the human spine, $P$ is the axial load, $L$ is the length of the beam column and $Q(x)$ is the transverse load imposed by the orthotic device. The boundary conditions to be coupled with the above differential equation are

$$y_1 \left(\frac{-L}{2}\right) = y_1 \left(\frac{L}{2}\right) = 0,$$

$$EI \frac{d^2 y_1}{dx^2} \left(\frac{-L}{2}\right) = k_s \frac{d^2 y_1}{dx^2} \left(\frac{-L}{2}\right),$$

$$EI \frac{d^2 y_1}{dx^2} \left(\frac{L}{2}\right) = k_i \frac{d^2 y_1}{dx^2} \left(\frac{L}{2}\right),$$
where \( k_s, k_i \) are the torsional spring constants of the springs that are part of the orthotic device. These are adjusted for each specific case and for each orthotic device. The combination between the parameters in the differential equation and on the boundary conditions are very general in nature and are supposed to be used to model several different types of orthotic devices, such as, the lumbar and thoracic pads of the Milwaukee brace, the built-in pad of the Boston brace, among others. Ideally, for each type of orthotic device, a different set of values for both \( k_s \) and \( k_i \) would be determined, depending on the setup and characteristics used, making this model a highly individualized and customizable model.

3. The biomechanical model for robotic traction devices

Robotic traction devices are one of the available methods to use as therapy for patients that have mild scoliotic spine. These noninvasive devices are designed to take most of the weight of the spine, while simultaneously applying a downward or upward traction force that will impact the original alignment of the spine. However, the effects of traction therapy on lumbar spine biomechanics are not well known and, to the best of the authors knowledge, there are no mathematical models that incorporate all the features of these devices. The robotic traction devices considered here are robotic traction chairs, where the patient takes a seated position in the chair, with his head fixed and the waist strapped to the chair. An example of these chairs is the Robotic Antalgic-Trak device. These chairs are designed to provide stabilization to the posterior thoracic rib arch, while simultaneously incorporating decompression and traction to the spine. This type of devices requires a great deal of different inputs from the operator. Some might appear to be standard, such as force to apply and session duration, whilst others require a much more detailed and thorough analysis, like the angle and point of application. However, without any model to calculate the force required, the adjustment of the traction depends solely on the patient feedback and levels of comfort. Therefore these inputs should be calculated from a model and determined on an individual level. However, no existent model takes all of these features and characteristics in consideration. The following model, as shown in figure 2, is now proposed.

![Figure 2](image-url)

**Figure 2.** The proposed biomechanical model of the spine for traction devices

In this model, \( P \) represents the axial load, \( R \) represents the traction force applied via the device and \( \alpha \), the angle under which the pull is made, measured between the \( x \)-axis and vector \( R \). This angle can vary between \( 0^\circ \) and \( 90^\circ \). One should also emphasize that this angle is to be applied in opposite direction of the curvature due to the idiopathic scoliosis. As in the model presented in [8], \( x \) represents position in the spine measuring \( L \). Hence the mathematical model proposed is given by the differential equation
\[ EI \frac{d^4 y_1}{dx^4} + P \frac{d^2 y_1}{dx^2} = -P \frac{d^2 y_0}{dx^2} - R \cos(\alpha), \quad x \in \left[ -\frac{L}{2}, \frac{L}{2} \right] \]  

along with the boundary conditions

\[ y_1 \left( -\frac{L}{2} \right) = y_1 \left( \frac{L}{2} \right) = 0, \]

\[ EI \frac{d^2 y_1}{dx^2} \left( -\frac{L}{2} \right) = 0, \]

\[ EI \frac{d^2 y_1}{dx^2} \left( \frac{L}{2} \right) = k_i \frac{d^2 y_1}{dx^2} \left( \frac{L}{2} \right), \]

where \( k_i \) is given by

\[ k_i = \frac{3EI}{L_i}, \]

as suggested in [8] and \( L_i \) represents the length of the inferior portion of the spine not included in the scoliotic curve. Also \( k_i = 0 \), as the upper portion of the spine is considered to be unsupported or subject to any force/pressure form the device. In robotic traction devices similar to this one, the traction force, \( R \), can be applied downwards or upwards. In this particular case, we assume the force is being applied downwards. A similar model can be obtained if the force is applied upwards. Also, the angle \( \alpha \), is an adjustable parameter on the device. We consider, as in the device, \( \alpha \) to be the angle between the \( x \) and \( y \) axis. The interaction between \( R \) and \( \alpha \) make it possible for the traction force to be applied on a wide range of angles. To better illustrate the full link between all the variables, parameters and applicability of the model, a test case is presented next.

4. Modeling a test case on a robotic traction device

As in most applications, adapting the theoretical model to a specific case requires a great combination of techniques. The objective of this section is to show how the parameters can interact and on top of that, how the model can be obtained and constructed for each individual. For this particular test case we consider a 43 year old male with a mild scoliotic initial curvature, as shown in the figure 3. The details of the specific parameters are shown in table 1.

| Parameter                               | Value    |
|-----------------------------------------|----------|
| Age                                     | 43       |
| Weight                                  | 78 kg    |
| Gender                                  | Male     |
| Spine length (L)                        | 58 cm    |
| Bending stiffness (EI)                  | 15.1 Nm^2|
| Angle (\( \alpha \))                   | 0°       |
| Inferior portion of the spine \( L_i \) | 5 cm     |
| Axial load (P)                          | 37 N     |
| R (maximum load advised)                | 255 N    |

**Table 1.** Specific parameters for the test case
The value for the bending stiffness, \( EI \), has been the subject of several different studies. In this paper we consider the value proposed in both \([4, 5]\), which is the mean value for a 43 year old male. Later in this paper a discussion in terms of the angle, \( \alpha \), and its impact will be considered, however initially for the first simulation we assume that the traction force applied is strictly downward, making \( \alpha = 0 \).

**Figure 3.** Subject MRI - test case

As shown by (2), in order to obtain \( y_1 \), which is the solution of the problem (2)-(3), \( y_0 \), the initial displacement must be determined first. This process was done using a curve fitting process. The value obtained for this particular individual was

\[
y_0(x) = -1.0798x^3 + 0.0364x^2 + 0.1883x + 0.0276.
\]

In addition, since due to the seating position, a portion of the weight of the head still impacts on the spine, the axial load \( P \), was not excluded from the model and was considered to have the same impact as in \([7]\). This value, which is calculated taking in consideration the subject’s weight, was estimated to be \( P = 36.9312216 \ N \). Therefore, considering all the specific parameters, equation (2) becomes

\[
15.1 \frac{d^4 y_1}{dx^4} + 36.9312216 \frac{d^2 y_1}{dx^2} = -36.9312216 \frac{d^2 y_0}{dx^2} - R \cos(\alpha), \quad x \in \left[ -\frac{L}{2}, \frac{L}{2} \right], \alpha \in [0, 90]
\]

Similarly, the boundary conditions become

\[
y_1 (-0.29) = y_1 (0.29) = 0,
\]

\[
15.1 \frac{d^2 y_1}{dx^2} (-0.29) = 0,
\]

\[
15.1 \frac{d^2 y_1}{dx^2} (0.29) = 906 \frac{d^2 y_1}{dx^2} (0.29).
\]

The total lateral displacement, \( y(x) \), can then be determined and is given by
\[ y(x) = -0.00186717139 x R + 1.751291904 \sin \left( \frac{49 \sqrt{5806554} x}{75500} \right) 
- 0.034101777 \cos \left( \frac{49 \sqrt{5806554} x}{75500} \right) + 0.01166819341 R 
+ 0.00123585514 \sin \left( \frac{49 \sqrt{5806554} x}{75500} \right) R 
- 0.034101777 \cos \left( \frac{49 \sqrt{5806554} x}{75500} \right) R 
+ 1.68607906 \times 10^{-11} x^2 - 2.548421660 x - 0.01353868023 x^2 R 
+ 0.0613155274 \] (7)

Let us emphasize that the function, \( y(x) \), depends on \( x \), the point of application and also on \( R \), the traction force to be applied. This interaction can be illustrated by the graph shown in figure 4, where \( x \in \left[ -\frac{L}{2}, \frac{L}{2} \right] \) and \( R \in [0, 255] \)

Figure 4. Solution in terms of location, \( x \) and traction force, \( R \)

From the analysis of the solution (4) one can identify the maximum to be attained when \( x = 0.2526 \), for any value of \( R \). Plugging this information back in (4), we obtain the total lateral displacement, \( y \), but in terms of \( R \), as shown below

\[ y(R) = 0.01033267910 R + 1.751291904 \sin \left( 0.0001639396319 \sqrt{5806554} \right) 
- 0.034101777 \cos \left( 0.0001639396319 \sqrt{5806554} \right) 
+ 0.00123585514 \sin \left( 0.0001639396319 \sqrt{5806554} \right) R 
- 0.01171378479 \cos \left( 0.0001639396319 \sqrt{5806554} \right) R - 0.5824179791 \]

Equation (4) provides then the total lateral displacement, in terms of the traction force, \( R \). Bearing this in mind, one can now determine the total traction force necessary, for this specific
individual, so that the total lateral displacement of the spine, both initial and the one due to the axial and transverse loads, to be 0. For this specific case, the total traction force to be applied is then

\[ R = 18207 \, N. \]

Let us recall that this simulation was obtained for \( \alpha = 0^\circ \), however, \( \alpha \) is one of the adjustable parameters in the robotic traction devices. The seating chair of the device can have the angle of application changed, ranging from 0\(^\circ\) to 70\(^\circ\). These angle variations can be used for some patients where the aligned position at 0\(^\circ\) is not comfortable. However, the change in the angle of application has a real impact in the total traction force to be applied. Once the angle is changed, the total traction force to be applied increases, as shown in the graph 5.

\[ \text{Figure 5. Graph showing the relation between the angle, } \alpha \text{ and the traction force, } R. \]

As one can see from the graph, the relation between the two variables is highly nonlinear and the higher the angle applied, the higher the total traction force to be applied.

5. Conclusion
In this study, it was possible to obtain the model for robotic traction devices, based on equations (2)-(3). The advantage of such a model lies on the fact that each individual feature can be measured and the therapy plan can be designed, based on each patient’s characteristics, without the usage of any invasive technique and with minimal knowledge of the subject, since for the model application only age, gender and an MRI or radiography showing the scoliotic curve are necessary. By doing so, one can obtain the total value of the traction force to be applied, necessary for the scoliotic curve to be eliminated. This total value obtained is a threshold value, meaning that for instance in our test case, a total force of 18207 N, would have to be applied in total for the scoliotic curve to be eliminated. For each therapy session, a maximum traction force of 40% of the body weight is recommended. Meaning that in our test case a maximum of 410 N is recommended per therapy session. This means that the patient would have to take sessions in the traction device, until a total threshold of 18207 N of force is accumulated. This information can and should be used to clearly identify \emph{a priori}, from the diagnosis stage, which cases can be considered for therapy using robotic traction devices. In this test case, it clearly shows that the traction device alone cannot be seen as a therapy to eliminate the scoliotic curve. However, for mild cases of scoliosis, the total traction force is considerably smaller. For those, the robotic traction device can be seen as a valid therapy. One of the future points of this research focus on determining the exact amount of force that is transferred after each session and what percentage is carried forward for the next sessions. In this way, the exact number of sessions can, in future, be determined, for each patient.
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