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Article

Biomechanical Analysis of Scoliosis Adjusted by Screw Fixation System with Finite Element Analysis

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Abstract. Adolescent Idiopathic Scoliosis is the most common type of scoliosis. The popular scoliosis treatment is scoliosis bracing or surgical treatment. The Cobb method is generally used to measure the scoliosis curvature angle for the surgeon in order to plan the treatment process. In addition, the Cobb angle of 40 degrees often creates a difficulty for surgeons in selecting the suitable treatment for the patients because the Cobb angle of 40 degrees is, in general, indicated as too large for scoliosis bracing although is not large enough to be indicated for surgical treatment. Therefore, this research investigated the relationship between the deformity of the Cobb angle between 30-70 degrees adjusted by the screw fixation system and evaluated the maximum equivalent of total strain distribution on the 3D models using the finite element analysis. All model cases were calculated with nonlinear ligament forces. The result showed a correlation between larger Cobb angles with higher maximum equivalent of total strain occurred on the vertebra, mainly resulted from the Rebound Force. The larger Cobb angle has resistance from the tendon and the muscles against the restoring force of the fixation devices adjusting the curvature of scoliosis. For this reason, the scoliosis patients with small Cobb angle are advised to be treated with surgery before the Cobb angle reaches 70 degrees in order to reduce the risk of damage on the vertebra, the fixation device, and the unsuccessful result of surgery.

Keywords: Scoliosis, screw fixation system, finite element analysis.

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1. Introduction

Spine is the most significant structure of the human body. The scoliosis, spinal deformity of lateral curvature, is mostly occurred in adolescents and adults. The patient of scoliosis who has the curvature of scoliosis larger than 30 degrees should be diagnosed by a surgeon for an appropriate method of treatment suitable for each level of deformity [1].

The curvatures of scoliosis deformity under 30 degrees almost never progress, the curves around 40 degrees may not progress, and the curves over 50 degrees are at great risk for progression. The angle of spinal deformity ranges between 30-50 degrees; it remains arguable that which the Cobb angle size determines whether the patient should undergo a surgery. Therefore, this research investigated the relationship between the deformity of the Cobb angle between 30-70 degrees adjusted by the screw fixation system, and the results of the evaluation of strain distribution using the finite element analysis.

The research was aimed to investigate the correlation between scoliosis (S-Shape) treatment using screw fixation system, and strain distribution on the vertebra that will help surgeons identify the suitable treatment for scoliosis patient with the curves between 30-70 degrees, with the idea of the patients having better daily living quality than before receiving the treatment.

2. Materials and Methods

Three-dimensional models studied in this research is the Thai vertebral column, intervertebral disc and screw fixation system.

2.1. Thai Vertebral Model

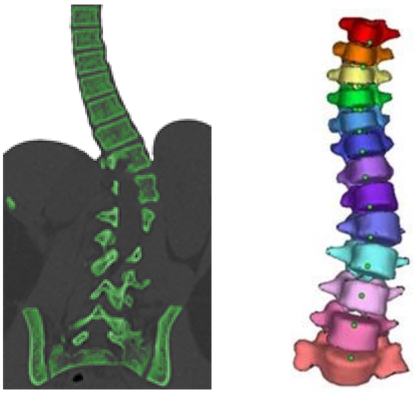
A three-dimensional model of vertebral column was scanned by computerized tomography (CT) scanner, analyzed, and reconstructed with ITK-SNAP program [2-4]. Fig. 1(a) showed the CT data of Thai scoliosis reconstructed by ITK-SNAP program and Fig. 1(b), the 3D model.

2.2. Intervertebral Disc Models

The three-dimensional model of the intervertebral disc was recreated from SolidWorks CAD software, in reference to the actual anatomy of the human spine. The intervertebral disc models consisted of annulus fibrosus and nucleus pulposus.

2.3. Screw Fixation System Models

After the surgery process, the screw fixation system would be used to adjust, fix the spine position, and correct the scoliosis deformity. The models of the screw fixation system were constructed by SolidWorks CAD software. In this research, the mono-axial of "Moss Miami" type was used, with an outer diameter of 5.00 mm, a core diameter of 3.03 mm, a pitch of 2.48 mm, a proximal root radius of 2.54 mm, a distal root radius of 2.54 mm, a proximal half angle of 33.17°, a distal half angle of 27.67°, and a thread width of 0.19 mm and a length of 30 mm [5, 6]. The material property of screw fixation system was assumed as the titanium alloy as shown in Fig. 2.



(a) (b)

Fig. 1. Thai vertebral column: (a) CT data of Thai scoliosis reconstructed with ITK-SNAP program and (b) Three-dimensional model of Thai vertebral column model [5].

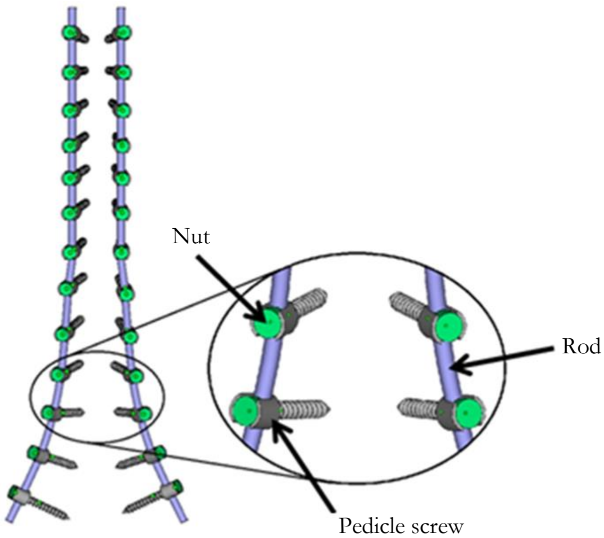


Fig. 2. Three-dimensional models of screw fixation system.

2.4. Rebound Force

Adjusting the scoliosis to a normal curvature is similar to moving the scoliosis into a new position, aligning with the central axis of the body in coronal plane. By fixing the spine in this position with screw fixation system, transverse force occurred, which varied directly to the distance, is called "Rebound Force (RF)"

2.5. Cases Analysis

All cases in this research, analyzed by the Finite Element Analysis, were aimed to evaluate the equivalent of total strain distribution on Thai normal curvature vertebral column, Thai scoliosis deformity and Thai scoliosis deformity adjusted by screw fixation system. The case analysis focused on S-shape scoliosis, with the size of Cobb angle at the top curvature deformity greater than the bottom curvature. The acting load focused on the posture of flexion or forward bending because this posture made the greatest pressure on the spine of patient [7]. The cases analysis is shown in Table 1 and the example of creating the three-dimensional model of S-shape scoliosis 70/60 degrees by measuring the scoliosis curvature angle with the Cobb method is shown in Fig. 3.

Table 1. The conditions of all cases analysis.

Case	Classifications of Spinal Curvature	Degree of Spinal Curvature (Top/Bottom Curvature Deformity)
1	Normal curvature vertebral column	0 degree
2	Scoliosis deformity	S-shape (24/14 degrees)
3	Scoliosis deformity adjusted by screw fixation system without Rebound Force	S-shape (24/14 degrees)
4	Scoliosis deformity adjusted by screw fixation system with Rebound Force	S-shape (24/14 degrees) with RF
5	Scoliosis deformity adjusted by screw fixation system with Rebound Force	S-shape (30/20 degrees) with RF
6	Scoliosis deformity adjusted by screw fixation system with Rebound Force	S-shape (35/25 degrees) with RF
7	Scoliosis deformity adjusted by screw fixation system with Rebound Force	S-shape (40/30 degrees) with RF
8	Scoliosis deformity adjusted by screw fixation system with Rebound Force	S-shape (45/35 degrees) with RF
9	Scoliosis deformity adjusted by screw fixation system with Rebound Force	S-shape (50/40 degrees) with RF
10	Scoliosis deformity adjusted by screw fixation system with Rebound Force	S-shape (55/45 degrees) with RF
11	Scoliosis deformity adjusted by screw fixation system with Rebound Force	S-shape (60/50 degrees) with RF
12	Scoliosis deformity adjusted by screw fixation system with Rebound Force	S-shape (65/55 degrees) with RF
13	Scoliosis deformity adjusted by screw fixation system with Rebound Force	S-shape (70/60 degrees) with RF

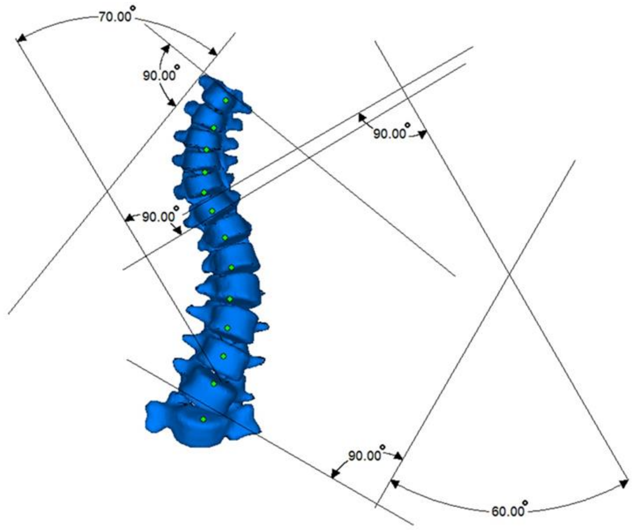


Fig. 3. Three-dimensional models of S-shape scoliosis (70/60 degrees).

2.6. Material Properties

Material properties of cortical bone, intervertebral disc, spinal ligaments and all implants were assumed to be homogeneous, an isotropic and linear elastic. The specification of materials properties is shown in Table 2.

Table 2. The materials properties of spine, ligaments and implants [8-10].

Material	Elastic Modulus (MPa)	Poisson's Ratio
Cortical bone	14,000	0.300
Disc-Annulus	4.2	0.450
Disc-Nucleus	1.0	0.499
Titanium alloy	110,000	0.300
Anterior longitudinal ligament (ALL)	Nonlinear	-
Posterior longitudinal ligament (PLL)	Nonlinear	-
Ligamentum falvum (LF)	Nonlinear	-
Capsular ligament (CL)	Nonlinear	-
Interspinous ligament (ISL)	Nonlinear	-
Supraspinous ligament (SSL)	Nonlinear	-

2.7. Loading and Boundary Condition

All models were representing Asian woman with height and weight of 150 cm and 50 kg respectively and were pressed with axial load from the weight of the head 35.80 N and flexion 4.2 N.m acted on the upper of the fifth thoracic vertebra (T5) and at the bottom of the fifth lumbar vertebra (L5) was fixed [11-13]. In addition, Rebound Force was added to the twelfth thoracic vertebra (T12), the position where the greatest distance from the adjustment of the curvature of scoliosis deformity occurred when adjusted by screw fixation system. The boundary condition of the middle of thoracic to thoracolumbar is shown in Fig. 4.

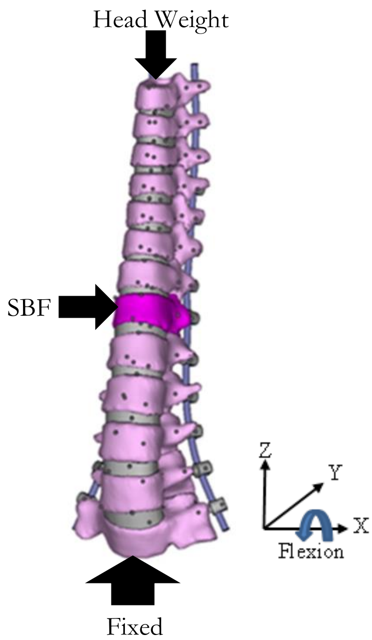


Fig. 4. The boundary condition of the middle of thoracic to thoracolumbar.

The Rebound Force calculated from Hooke's law equation [14], states that

$$F_{Spring\ back} = kx$$

where

$F_{Spring\ back}$ = Rebound Force (N)

k = Stiffness from Facet Capsulary Ligament (CL)
The stiffness from CL of Thoracic = 24.889 N/mm
The stiffness from CL of Lumbar = 19.646 N/mm

x = Distance when bending the scoliosis spine back to normal straight (mm)

From the Hooke's law equations, the Rebound Force values of case 4 to 13 under flexion condition is shown in Table 3.

Table 3. Rebound Force in case analysis.

Case	Degree of Spinal Curvature	Rebound Force (N)
4	24°/14°	491.38
5	30°/20°	496.48
6	35°/25°	510.92
7	40°/30°	546.26
8	45°/35°	557.44
9	50°/40°	581.11
10	55°/45°	616.12
11	60°/50°	641.54
12	65°/55°	657.04
13	70°/60°	702.46

2.8. Mesh Generation

MSC Marc software was used to generate the mesh models and the four-node tetrahedral element was used in this research. The total number of nodes and elements of the model were as follows: 73,939 nodes and 281,780 elements for Normal model, 72,584 nodes and 277,038 elements for Scoliosis, and 1,087,751 nodes and 4,892,176 elements for Scoliosis adjusted by screw fixation system.

2.9. Convergence Testing

Convergence testing was a process used to find the smallest size of mesh element, the most suitable and the least time consumed to give the exact solution [15, 16]. By varying the mesh model of pedicle screw sizes, ranging from 0.1 to 0.7 mm, it was found that 0.3 mm was optimum size that was to be used in this research. The relations between mesh sizes and maximum von Mises stress on pedicle screw is shown in Fig. 5.

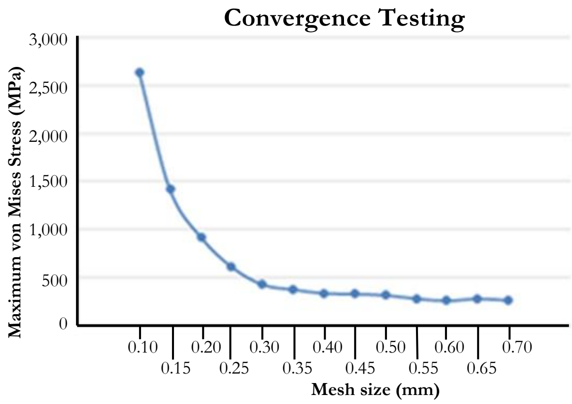


Fig. 5. The relations between mesh sizes and the maximum von Mises stress on pedicle screw model.

3. Result and Discussion

The results highlighted the maximum equivalent of total strain distribution on thoracolumbar (T5-L5) of Thai normal curvature vertebral column, Thai scoliosis deformity, Thai scoliosis deformity adjusted by screw fixation system with and without Rebound Force applied at T12 for 10 different models under flexion condition.

3.1. Comparison of the Model with and without Rebound Force

The results were divided into 2 main cases as follows: the first case was the models without Rebound Force of Thai normal curvature vertebral, Thai scoliosis deformity, Thai scoliosis deformity adjusted by screw fixation system. The maximum equivalent of total strain on L1 of Thai normal curvature vertebral column was 85.52 με, 50.35 με for Thai scoliosis deformity, and 290.24 με for Thai scoliosis deformity adjusted by screw fixation system.

The second case was the models of Thai scoliosis deformity adjusted by screw fixation system with 10 different values of Rebound Force. The maximum equivalent of total strain on L1 of Thai scoliosis deformity adjusted by screw fixation system with Rebound Force is shown in Table 4.

Table 4. The maximum equivalent of total strain of Thai scoliosis deformity adjusted by screw fixation system with Rebound Force.

Case	Degree of Spinal Curvature	The Maximum Equivalent of Total Strain (με)
4	RF 24°/14°	20,527
5	RF 30°/20°	22,257
6	RF 35°/25°	23,062
7	RF 40°/30°	22,320
8	RF 45°/35°	22,713
9	RF 50°/40°	25,669
10	RF 55°/45°	24,941
11	RF 60°/50°	25,762
12	RF 65°/55°	26,096
13	RF 70°/60°	28,043

The equivalent of total strain distributed on L1 under flexion condition of Thai scoliosis deformity adjusted by screw fixation system with Rebound Force are shown in Fig. 6.

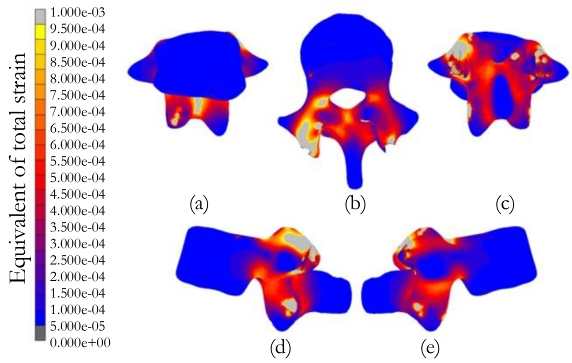


Fig. 6. Equivalent of total strain distributed on L1 of Thai scoliosis deformity adjusted by screw fixation system with Rebound Force: (a) Anterior view, (b) Top view, (c) Posterior view, (d) Left side view and (e) Right side view.

3.2. Screw Fixation System

The general surgical treatment has a set of spinal fixation devices to stabilize after surgery called "screw fixation system". The von Mises stress occurred on the screw fixation system in all cases did not exceed the yield strength, although 5 out of 13 cases had the maximum equivalent of total strain occurred on L1 vertebra that were approximately equal to or greater than 25,000 με, which induced possibility of bone fracture [17, 18]. Moreover, the concentrate stress occurred around the neck of the pedicle screw, as shown in Fig. 7, because this area was a central location between the pedicle region of vertebra and the screw rod, where the energy between bone and implant transferred [19-25].

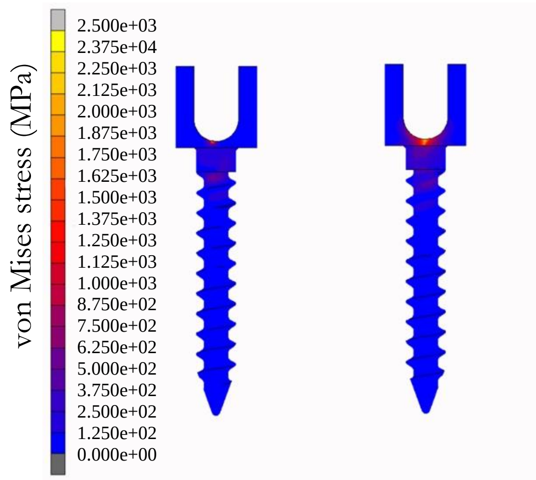


Fig. 7. The von Mises stress occurred on the left pedicle screw that fixed on T12 in case RF 70/60°: (a) Upper view and (b) Lower view.

3.3. Model Validation

Model validation was the process of validating 3D models in this research. It was divided into 2 main steps: creating the mechanical test kit and mechanical testing.

3.3.1. The mechanical test kit

The first step was to create the mechanical test kit, which simulated virtual screw fixation system on the human spine. The mechanical test kit used Aluminum alloy 5083 (Al 5083), cuboid size 45×50×25 mm, 3 pieces for substitute of the thoracic vertebrae. For the 2 rods of screw fixation system, the diameter size was 5 mm and the length was 80 mm, Al 5083. All the pedicle screws used on this mechanical test kit were genuine medical devices and fixation process was supported by a surgeon. All the 6 pedicle screws made from Titanium alloy, had an outer diameter of 6 mm, and the length of 45 mm. The procedure of assembling a mechanical test kit was as follows:

First step, drilling a center hole before screwing with the pedicle screw by using the drill press. Two drilled holes had a diameter 5.9 mm and depth 48 mm, both the left and right side of the Aluminum cuboid. Second step, tightening the pedicle screw by using the torque wrench. The last step, assembling the rods to the mechanical test kit by inserting the rods into the slot on the back of the pedicle screw and fixing tightly with nuts.

3.3.2. Mechanical validation testing

The four strain gauges were attached on the rod of the mechanical test kit to measure the stain value; the data were collected by the Keysight 34972A data logger. The compressive force applied to the top of mechanical test kit by the Universal Testing Machine, which generated the constant compressive load at 1±0.1 N at the top of mechanical test kit as shown in Fig. 8.

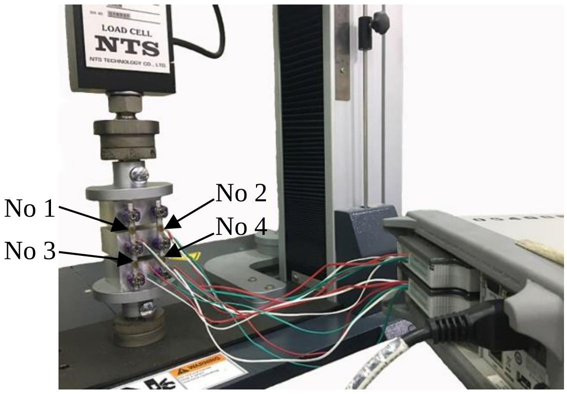


Fig. 8. Mechanical test kit installed in Universal Testing Machine (UTM) for validated model.

During the UTM running, the data logger also recorded the values of strain that occurred on both rods at the strain gauge attachment and transformed to von Mises stress. All strain values and von Mises stress are shown in Table 5.

Table 5. The strain values on the rods at strain gauge attachment and von Mises stress.

Strain Gauge	ε_a $(\mu\varepsilon)$	ε_b $(\mu\varepsilon)$	ε_c $(\mu\varepsilon)$	von Mises Stress (MPa)
1	0.001433	0.001380	0.001393	149.07
2	0.001561	0.001552	0.001481	165.10
3	0.001554	0.001538	0.001543	163.84
4	0.001821	0.001561	0.001536	180.17

The finite element model of mechanical test kit was created and simulated to evaluate the von Mises stress on the rods. The model had a total of 1,034,861 nodes and 4,874,142 elements. The material properties of Al 5083 consisted of elastic modulus 71,000 MPa and Poisson's ratio 0.33. The model was compressed with distribution load 1 N at the top of the first Aluminum cuboid and was fixed at the end of the third box. The von Mises stress distribution on the model is shown in Fig. 9.

The comparison of von Mises stress from the four strain gauges and finite element model is shown in Fig. 10. The percentage errors at position No 1, 2, 3 and 4 were 3.701%, 7.221%, 4.542% and 3.270% respectively. It can be concluded that the percentage error from validation of 3D model was "acceptable" and the finite element model was reliable [26].

The strain concentration occurred around the screw hole because it was a connecting area between the vertebrae and the screw fixation system that transmitted and exchanged the stress and strain between the spine and the fixation device. Therefore, if the stress or strain concentration occurred on this area exceeds the limit, it can cause damage to bones and implants [19, 27]. Furthermore, the previous studies suggested that if a pedicle region fracture occurs, the diameter and length of the pedicle screw must be changed accordingly; the diameter and length of new pedicle screw must be greater than the old screws that were fixed before the fracture, or else, the fractured crews must solely be replaced with longer screws [28-31].

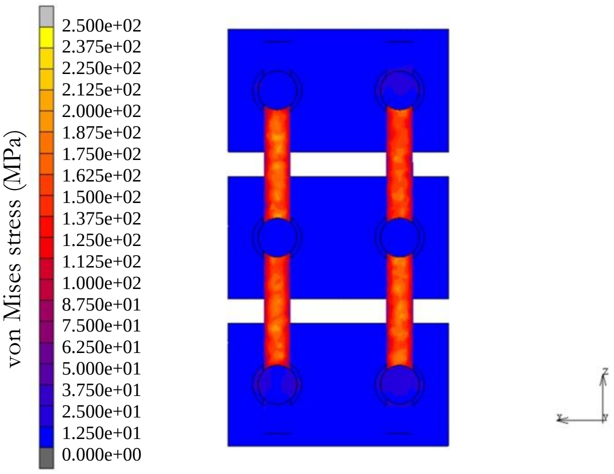


Fig. 9. The von Mises stress distribution on both rods.

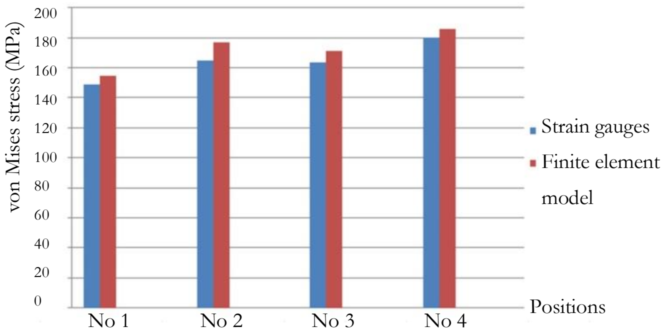


Fig. 10. The comparison of von Mises stress from strain gauges and finite element model.

In addition, the results of the finite element analysis showed that the equivalent of total strain distribution increased more on L1, when the effect of Rebound Force was analyzed together with the movement of scoliosis adjusted by screw fixation system. This could be explained by Hooke's law equation [14], that is, when the deformity of spinal curvature was adjusted by the surgeon for the suitable degree for each patient – the degree closest to the normal curvature – an invisible resistance similar to spring rebound occurred from surrounding soft tissues such as Supraspinous Ligament (SSL) and Intertransverse Ligament (ITL), thus, the strain increased. SSL and ITL resisted the movement resulted from the deformity correction of the curvature degree of scoliosis, and pulling the scoliosis deformity adjusted by screw fixation system back to the original state before the surgery. Therefore, the screw fixation system is obliged, in order to maintain the stability of the surgery treatment [32, 33], similar to the case of patients who were required to wear the retainers, after the orthodontic treatment was finished [34, 35].

Moreover, uncertainty about the choice of treatment for scoliosis patients whose Cobb angle ranged between 40-50 degrees, remained a concern for surgeons [36]. Hence, when considering the relationship between the maximum equivalent of total strain and the curvatures of scoliosis deformity measured by Cobb method in Table 4, it is found that, as the Cobb angle increased, the maximum equivalent of total strain occurred on L1 vertebra, as in this case study, L1 vertebra was the center of scoliosis curvature, tended to increase accordingly.

From the relationship between the maximum equivalent of total strain and the Cobb angle in Table 4, it can be described that, when the Cobb angle reached 40 degrees, it would increase the resistance force when treating the scoliosis deformity back to the normal spine, from the tendons and muscles. The patients whose Cobb angle were greater than 40 degrees or the patients with very large Cobb angles, the resistance against the bending force of the fixation device will be increase even more. This may result in lower chance of successful operation treatment and more chance of damage on the implants after surgery. Therefore, the scoliosis patients with a small Cobb angle should be treated with surgery before the Cobb angle reaches 40 degrees to reduce the risk of damage to the fixation device and an undesirable result of surgery.

As for the scoliosis patients whose Cobb angle reached more than 40 degrees, or with prolonged scoliosis without the surgical treatment, the Rebound Force resulting from a greater Cobb angle of scoliosis had a greater impact to vertebra. When the patients decided to undergo with surgical treatment, they would require a longer recovery period because human bones takes at the least 3-6 months to recover [37, 38]. The early stage after surgery, patients should be disciplined to wear a brace to help and support the muscles and tendons to remain as stable as possible and, most importantly [39-41], the brace reduced the impact of Rebound Force trying to bring the scoliosis back to pre-treatment state. In this regard, the patients must be careful with their body movements in the manner of turning or twisting, because rotation or twist will cause more torque, resulting in more stress as well, according to the bending stress and the torsion shear stress.

4. Conclusion

The origin of this research came from many difficulties concerning the angle of scoliosis curvature measured by the Cobb method in the range of 40 degrees because this angle size was too great for bracing treatment, but not large enough for surgical treatment. This creates hesitation for surgeons to decide the appropriate treatment for scoliosis patients. All the information obtained from this research and the main points were summarized as follows:

This research focused on the scoliosis deformity (S-shape) that occurred on middle thoracic and thoracolumbar spine. Adolescent Idiopathic Scoliosis (AIS) is the most common type of scoliosis and more common in females than males. The popular treatment is bracing and surgical treatment; wearing a brace is suitable for patients whose skeletons have not matured or scoliosis patients whose Cobb angle is less than 40 degrees. During the treatment process, for the most effective treatment results, patients should wear a brace for at least 16-23 hours daily. As for the surgical treatment, it is a surgery to adjust the deformity angle of scoliosis patients using the screw fixation system to help maintain stability after surgery.

The result was found that the maximum equivalent of total strain occurred on the vertebra, the center of scoliosis curvature, tended to increase when the Cobb angle increased. For these reasons, the scoliosis patients with a small Cobb angle, but it is likely that surgery will be required in the future, should be treated with surgery before the Cobb angle reached 40 degrees to reduce the risk of damage on the fixation device and the possibility of failed surgery treatment because the larger Cobb angle had resistance from the tendons and the muscles that rebounded bending force of the fixation devices adjusting the curvature of treated scoliosis.

Therefore, the scoliosis patients whose Cobb angles were greater than or equal to 40 degrees should be treated with the appropriate treatment from the surgeon as soon as possible to adjust the angle of scoliosis back to normal curvature, in order to reduce the Cobb angle progression. The most important reasons shall involve better physical health, and mental health of the patient after the surgery compared to before the surgery. However, during the first stage after surgery, the patients should be careful of body movements because natural human bones take at the least 3-6 months to recover; patients should have disciplines wearing a brace to help support the muscles and tendons to remain as stable as possible, to reduce the impact of Rebound Force, trying to bring the scoliosis back to pre-treatment state.

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Conflict of interest

The authors declare that they have no conflict of interest.

Ethical approval

This research was a part of the project "Biomechanical Study of Scoliosis Adjusted by Screw Fixation System" and has been reviewed and approved by the Committee on Human Rights Related to Research Involving Human Subjects, Faculty of Medicine, Ramathibodi Hospital, Mahidol University, based on the Declaration of Helsinki.

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