Acta of Bioengineering and Biomechanics
Vol. 21, No. 2, 2019

Original paper
DOI: 10.5277/ABB-01282-2018-05

An evaluation of the efficiency of endpoint control on the correction of scoliotic curve with brace. A case study

MOHAMMAD KARIMI[1, 2], TIMON RABCZUK[2]*, MAULUDIN LUTHFI[2],
BABAK POURABBAS[3], AMIR ESRAFILIAN[4]

[1] Rehabilitation Sciences Research Center, Shiraz University of Medical Sciences, Shiraz, Iran.
[2] Department of Geotechnical Engineering, Tongji University, Shanghai, China.
[3] Bone and Joint Diseases Research Center, Shiraz University of Medical Sciences, Shiraz, Iran.
[4] Eastern Finland University, Kuopio, Finland.

Purpose: The use of braces is one of the conservative treatment approaches recommended for scoliotic subjects. However, the main question posted here is how to improve the efficiency of braces to control the scoliotic curve or to decrease its progression. The aim of this study was to evaluate the efficiency of various boundary conditions (endpoint control) of brace on the correction of scoliotic curves. *Method*: CT scan images of a scoliotic subject, with double lumbar and thoracic curves, was used to produce 3d model of spine. The correction of spine (decrease in scoliotic curves) was determined following the use of transverse (lateral-to-medial direction) and the combination of transverse and vertical (upward-directed force, traction) forces on spine in Abaqus software. The effects of pelvic fixation (pelvic basket of a brace) on both sides (basket enclosed pelvic in both sides), on one side (basket enclosed the pelvis in only one side), and fixation of lumbar (part of the brace encircled the lumbar area) were evaluated in this study. *Results*: The results of this study showed that the effect of vertical forces (traction) was more than that of transverse force. Moreover, the combination of vertical and transverse forces on lumbar and thoracic curves correction was more than that of other conditions (only transverse forces). The best correction was achieved with lumbar fixation and with combination of vertical and transverse forces. *Conclusions*: The use the combination of vertical and transverse forces may be suggested to correct the scoliotic curve. Moreover, the efficiency of lumbar fixation in frontal plane seems to be more than pelvic fixation to correct scoliotic curve. The outputs of this study can be used to design new braces for scoliotic subjects.

Key words: *scoliosis, brace, finite element analysis, boundary condition*

1. Introduction

Scoliosis is defined as lateral curvature of the spine, associated with a change in the alignment of vertebras in sagittal, frontal and transverse planes [28]. The incidence of scoliosis deformity varies between 2 and 13.6%. Although the etiology of this disorder is not well-understood, some factors regarding the etiology of scoliosis have been mentioned. Some reasons such as genetics, growth hormonal dysfunction and bone mineral density change, abnormality in body part tissue (vertebral bone, and supportive ligaments), abnormal platelet calmodulin levels, biomechanical factors and central nervous system abnormalities influence the incidence of this disorder [1].

Based on the age of the subject, severity of the curve and the progression rate of the curve, various treatment approaches have being used for scoliotic subjects, including conservative treatment and surgery [11], [13]. The main conservative treatment used for this group of the subjects are use of braces (which is mostly used for juvenile and adolescent idiopathic scoliosis with a curve between 25–45 degrees), physical therapy

* Corresponding author: Timon Rabczuk, Department of Geotechnical Engineering, Tongji University, Shanghai, China, 1239 Siping Road, Shanghai 200092, P.R. China. E-mail: timon.rabczuk@uni-weimar.de

Received: December 24th, 2018
Accepted for publication: April 3rd, 2019

exercise (physiotherapeutic scoliosis specific exercise, mobilization technique and manual therapy), and Youg [15], [19]. Some braces, such as Milwaukee brace, Boston, Rosenberger, Wilmington, Providence, Charleston bending brace, Cheneau and Lyon braces, are some of the common used braces in this regard. Bracing can be classified into night time bracing, soft bracing, part time rigid bracing and full time rigid bracing [19]. The efficiency of these braces depends on the severity of the curve, type of the curve, location of the curve and also on time and duration of brace usage [4]. Based on the results of available studies, braces are mostly priscripted for scoliotic curve between 25 and 45 degrees [4], [19]. They may control the progression of the curve, but may not be able to influence the natural history of the curve significantly.

The design of the available braces is based on the application of transverse (lateral to medial), vertical (traction), and the combination of both vertical and transverse forces, which are applied mostly at the apex of the curve [12]. In some designs of the braces, such as in Milwaukee, the end points of the spine (pelvis and cervical) are immobilized by pelvic basket and cervical ring [5]. In contrast, in Cheneau brace, depending on the design, both or just one part of the pelvis should be immobilized [23]. Based on the available literature it is not possible to determine the correctability of the curve immediately following the use of the braces without follow-up (although it has been mentioned that the initial in-brace correction should be between 30–50% of the initial curve) [5], [19]. Moreover, it is not possible to check the correction, which can be achieved by the use of various braces and with various force configurations for each subject, immediately.

It should be noted that the main aim of using brace is to decrease the progression of the curve during growth period [11], [23]. Therefore, scoliotic subjects should use their braces for a long period of time [2]. Restriction of spinal motion, extra force applied on trunk and the problems associated with brace wearing are some of the main issues associated with brace use [6], [24]. Moreover, the efficiency of the brace seems to be controversial [5]. After a long period of time, the curves may be unchanged or may increase significantly (by surgically more than 5 degrees), and should be stabilized. Therefore, it is very important to have an approach to check the effects of various designs of braces and force configurations. The outputs of this approach can be used to improve the design of the available braces, and to have an effective approach to control the progression of the curve which finally improves the quality of the life of the scoliotic subjects and reduce the costs.

The use of finite element analysis is one of the methods recommended in this regard. Biomechanics used this method in 1972 to evaluate the mechanical properties of bones. However, Wynasly and Schulf used it to determine the correction achieved by active muscle force and passive brace structure in the subject with mid right thoracic scoliosis [14], [27]. The studies on FEA of spine nowadays available can be categorized into studies on the use of FEA on etiology of AIS, on brace treatment for the moderate deformities, the instrumentation treatment for sever deformities and the use of FEA to increase the sensitivity studies on FEA [27].

There are some studies on feasibility of the use of FEA to determine correction achieved follow the use of FEA [16], [22]. Based on the results of these studies, it can be stated that FEA is a feasible method to determine the correction which can be achieved follow the use of braces. There was a good agreement between the output of FEA and clinical outputs. However, most of these studies were carried out based on Boston brace [16]. Furthermore, the 3D model of the spine was produced based on X-ray images of spine and the assigned material properties obtained from cadaveric studies [27], [10].

Locations and the forces of the straps were the other parameters evaluated in the studies of FEA of spine [21]. Although most of these studies were done on Boston brace, the outputs showed that high thoracic pad reduces more efficiently both lumbar and thoracic scoliosis curves.

It should be emphasized that FEA consists of several steps including producing geometry of spine based on CT scan or X-ray images, assigning appropriate materials based on density of the element, mechanical properties, validation of the model, and stimulation of the final model [18]. Therefore, the final accuracy of the model and its feasibility to predict the output of treatment depends on the methods selected for doing of aforementioned stages. There are some issues associated with the available studies on use of FEA in the research related to scoliosis of spine. Most of the studies were from the models developed based on X-ray images. The validity of the models was not evaluated. Moreover, the material properties were based on the literature and from the data obtained from cadaveric studies. Last but not least was that the available studies was too limited and mostly focused on Boston brace.

Nowadays, there are lots of variation in the designs of new developed brace such as Cheneau, and Gensingen braces. The end point of these braces encircles the pelvic in one side or both sides. Moreover, the pattern of applying corrective forces varies significantly [19], [23]. There is no doubt that FEA can be used to predict the output of treatment with brace and also to evaluate the efficiency of various designs of braces and force configurations. However, due to limited number of studies there are some gaps which should be considered in the future studies which include:

1) lack of evidences on the effects of various force configurations (transverse, vertical or combination of both) and magnitudes on scoliotic curve correction,
2) lack of the effects of various endpoint control (half pelvic control or full pelvic control) in the design of the braces on scoliotic curve correction,
3) lack of the evidences on the efficiency of the combinations of force configurations and end point control on scoliotic curve corrections.

Therefore, the aim of this study was to evaluate the effects of various end point controls on scoliotic curve correction. The main hypothesis associated with this study was that use of various force configurations and end point controls influence the magnitude of scoliotic curve correction following the use of a brace.

2. Materials and methods

CT scan images of a scoliotic girl with age, weight and height of 12 year, 45 kg, and 1.62 m, respectively, were used in this case study. An ethical approval was obtained from Shiraz University of Medical Sciences ethical committee. The Cobb angles of scoliotic curve were 21 and 44.5 degrees in lumbar and thoracic, respectively. The subject had a right thoracic (44.5 degrees) and left lumbar (21 degrees) curves.

The effects of various boundary conditions (half or full pelvic basket) and the combination of various forces (transverse, vertical and combination of both) were evaluated in this study. This was done using Abaqus, and Mimics softwares.

Procedure

The computed scan images (CT-scan) of spine were used to create a 3D model. The images can be described as: The 2D parallel planes from the three (sagittal, coronal and axial) views of the spine with 512 × 512 pixel in a DICOM format (digital imaging and communication in medicine) [25]. Nowadays, CT scan images are a pixel maps of the linear X-ray attenuation coefficient of tissue. Mimics software (Materialize Interactive Medical Image Control system, version 19 for research, produced by Materialize Company, Belgium) was used to create 3D model of spine, based on CT scan images thorough the following steps:

1) thershoulding based on Hounsfield unit,
2) the use of region growing process to split the segmentation into separate parts (vertebras and disks),
3) creating 3D models based on generated region mask,
4) using remesh option to convert the files compatible with 3 Matic software.

It should be emphasized that the procedure was done separately for bone and disks.

Surface mesh was exported from Mimics software to 3 Matic software (version 19 for research). This software provides this capacity to change the format of mesh and to optimize it. The optimization of mesh was based on the ratio of side length to minimum side length of a triangle element (which should be no longer than 10), its minimum interior triangle (should be more than 20) and maximum interior angle (should be less than 120). The following steps were done to remesh the models:

1) the removal of sharp triangles,
2) the reduction of the outer surface details,
3) the reduction of total number of triangles,
4) optimizing triangular shapes and create a uniform mesh,
5) reduction of small triangles,
6) volumetric mesh.

The volumetric mesh of each components including bones (sacrum, iliac, sternum, vertebras and ribs) and disks were merged to produce a 3D meshed model of total spine. The final part was exported to Mimics software to assign the material properties.

Although in most of available studies on FEA of spine the material properties were obtained based on the literature data, in this study it was done based on outputs of Mimics software. Due to the use of this software it was possible to assign different material properties of bone and disks. The material properties of various parts of bones and disks were calculated based on the number of pixel in CT scan images. Mimics software defines a number of sampling points within each element and interpolates the gray level related to coordinate from the original CT scan. Based on various studies, gray level is proportional to apparent bone density. Based on this approach Young's modulus of elasticity was determined on a basis of density. The following equations were used to calculate the bone density and Young's modulus of elasticity from gray level [26].

$$\rho = -13.4 \pm 1017\, GV, \tag{1}$$

$$E = -388.8 + 5925\rho, \tag{2}$$

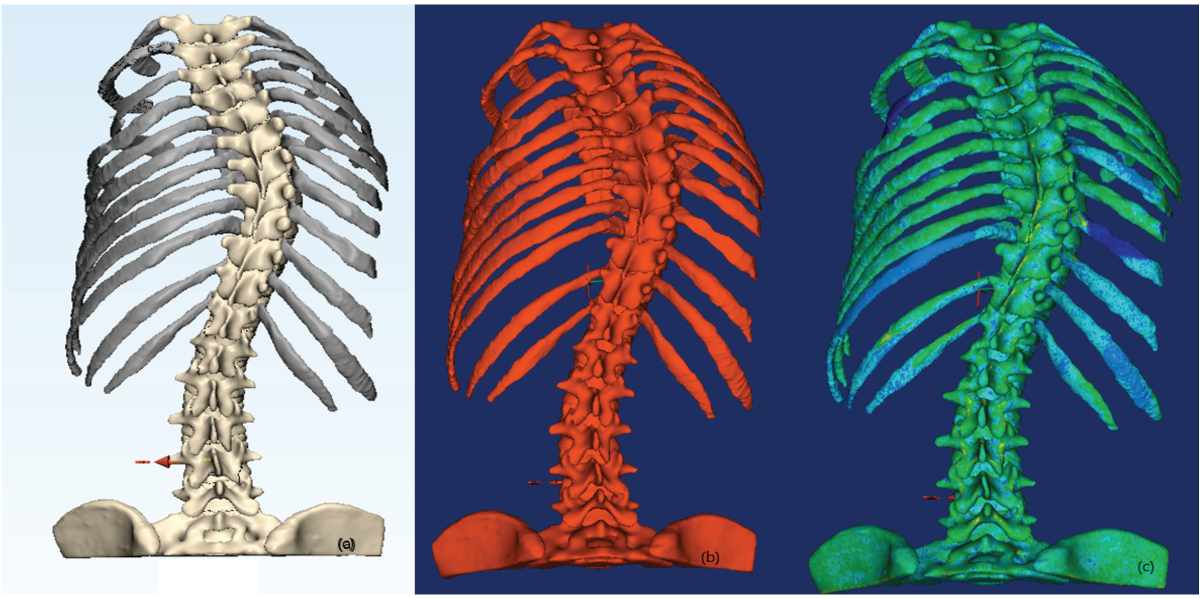

Fig. 1. The model developed based on CT scan images of the subjects:
(a) 3D model, (b) model with remesh, (c) with material assigned

where E is Young's modulus of elasticity, ρ is appearance bone density and GV is gray value [26]. The material properties were determined and assigned to the model. The final model was exported to Abaqus for FEA analysis. In Figure 1 the model developed in this research is shown.

Boundary conditions and force assignment

The pelvic (including sacrum and iliac bones in both right and left sides) (boundary condition 1), in one side (boundary condition 2) and lumbar vertebra (boundary condition 3) were selected in Abaqus software. Various force configurations and magnitudes were used in this study. In Figure 2, the model exported to Abaqus software with force and boundary conditions assignment is shown.

As it was already mentioned, the forces were applied on transverse and vertical planes. The magnitude of the forces, which in clinical situations are applied on the spine through the straps of the brace or brace structure, were determined based on the available studies. The magnitude of the forces applied on the spine varied between 0 and 100 N [16], [20], [22]. In Table 1 the various configurations of boundary conditions and forces used in this study are summarized.

The stress developed in the spine, and magnitude of the deformation was obtained from Abaqus software. Moreover, the correction of the scoliotic curves (lumbar and thoracic) was determined for each condition. It should be emphasized that the magnitude of correction achieved by various conditions was determined based on Cobb angle. However, the final results was reported based on the percentage of final correction achieved. In Figure 2 the location of the boundary conditions and the forces applied on the spine is shown.

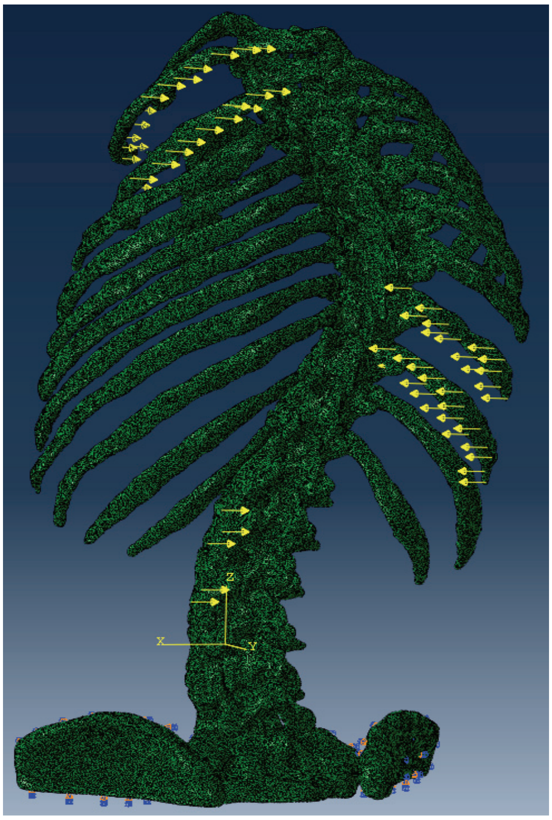

Fig. 2. The exported model in Abaqus with assigned force and boundary conditions

Table 1. The magnitude of the forces applied on the spine in various force conditions

Conditions	Force at thoracic apex [N]			Force at lumbar apex [N]			Force at upper part of thoracic curve			Force at Pelvic			Boundary part (endpoint control)
	(ML)	(AP)	(V)	(ML)	(AP)	(V)	(ML)	(AP)	(V)	(ML)	(AP)	(V)	
C1	50	0	0	–25	0	0	–25	0	0	0	0	0	Pelvic (both sides)
C2	75	0	0	–37.5	0	0	–37.5	0	0	0	0	0	Pelvic (both sides)
C3	100	0	0	–50	0	0	–50	0	0	0	0	0	Pelvic (both sides)
C4	50	0	50	–25	0	25	–25	0	25	0	0	0	Pelvic (both sides)
C5	75	0	75	–37.5	0	37.5	–37.5	0	37.5	0	0	0	Pelvic (both sides)
C6	100	0	100	–50	0	50	–50	0	50	0	0	0	Pelvic (both sides)
C7	50	0	0	–25	0	0	–25	0	0	0	0	0	Pelvic (one side)
C8	75	0	0	–37.5	0	0	–37.5	0	0	0	0	0	Pelvic (one side)
C9	100	0	0	–50	0	0	–50	0	0	0	0	0	Pelvic (one side)
C10	50	0	50	–25	0	25	–25	0	25	0	0	0	Pelvic (one side)
C11	75	0	75	–37.5	0	37.5	–37.5	0	37.5	0	0	0	Pelvic (one side)
C12	100	0	100	–50	0	50	–50	0	50	0	0	0	Pelvic (one side)
C13	50	0	0	0	0	0	–25	0	0	–25	0	0	Lumbar
C14	75	0	0	0	0	0	–37.5	0	0	–37.5	0	0	Lumbar
C15	100	0	0	0	0	0	–50	0	0	–50	0	0	Lumbar
C16	50	0	50	0	0	0	–50	0	50	–50	0	50	Lumbar
C17	75	0	75	0	0	0	–75	0	75	–75	0	75	Lumbar
C18	100	0	100	0	0	0	–100	0	100	–100	0	100	Lumbar

ML = mediolateral, AP = anteroposterior, V = vertical.

Optimization of the model: The optimization of the model was done based on three approaches including [10]:

1) comparison of the mechanical properties of spine structures of the model with available data from the literature,
2) comparison of the range of motion of the spine follow the forces applied on the spine with data available from the literature.
3) comparison of the scoliotic angles of the spine in FEA software with the angles obtained from CT scan images.

In order to evaluate the range of motion of total spine with ribs the following moment and force were applied on the spine [17].

- Bending force: 1.32N, applied on T1,
- Lateral bending force: 1.32 N, applied on T1,
- Rotational force: 1.65 Nm with 24 N compressive force.

Although it was a case study, the difference between the percentages of correction obtained in various boundary conditions was evaluated by the use of two-sample *t*-test. Shapiro–Wilk test was used to check the normal distribution of the data.

3. Results

The evaluation of the results of optimization model

The bone mineral density and Young's modulus of elasticity are summarized in Table 2. As can be seen from this Table, the Young's modulus of elasticity varied between 1.6 and 7.29 GPa for bone and between 0.334–0.936 GPa for intervertebral disk. The ranges of motion of the spine following the application of the aforementioned forces are shown in Table 3. The Cobb angle of lumbar curve based on CT scan images and FEA software were 20 and 21 degrees, respectively, compared to 45 and 44 for thoracic curve.

Table 2. The mechanical properties of material assigned to the model

Parameters	bone mineral density [kg/m^3]	Young's modulus of elasticity [GPa]	Poison ratio
Cortical Bone	$0.645–1.63 \cdot 10^6$	2.87–7.29	0.3
Spongy Bone	$0.36–0.494 \cdot 10^6$	1.6–2.2	0.3
Disk	$0.21–0.75 \cdot 10^6$	0.334–0.936	0.3

The maximum correction achieved with various forces and boundary conditions (Table 1) are summarized in Table 4. In this table, the maximum stress developed in spine are also presented.

Table 3. The range of motion (ROM) of spine between T1-T12 and T1-L5

Parameters	ROM by Flexion moment	ROM by Lateral bending moment	ROM by Rotation moment
T1–T12	11.6	10	10
T1–L5	3	9	10.4

Table 4. The percentage of the correction and maximum stress of spine structure follow the use of various force and boundary configurations

Conditions	Lumbar curve [%]	Thoracic curve [%]	Stress [MPa]
C1	1.8	0.45	79.5
C2	5.26	0	119.3
C3	2.17	0.65	178.9
C4	6.25	7.90	13.6
C5	1.54	0	110.8
C6	1.27	0.73	166.2
C7	4.08	2.69	75.65
C8	2.22	0.48	113.5
C9	0.62	12.51	170.2
C10	7.75	3.79	79.5
C11	6	9.66	119.3
C12	0.21	8.00	178.9
C13	11.18	12.83	79.5
C14	14.51	6.69	116.3
C15	4.40	3.58	155.1
C16	0.32	26.02	73.81
C17	2.22	13.51	110.7
C18	0.65	31.66	147.6

Table 5. The *p*-values of the comparison between the corrections of lumbar and thoracic parts with various boundary conditions

Comparison	Lumbar	Thoracic
TF1:TF2	0.314	0.12
TF1:TF3	0.04	0.02
TF2:TF3	0.03	0.3
TV1:TV2	0.2	0.1
TV1:TV3	0.05	0.01
TV2:TV3	0.1	0.02

TF1: Transverse force, boundary condition1, TF2: Transverse Force, Boundary condition 2, TF3: Transverse force, boundary condition3, TV1: Transverse and Vertical Forces, Boundary condition 1, TV2: Transverse and Vertical Forces, Boundary condition 2, TV3: Transverse and Vertical Forces, Boundary condition 3.

Although it was a case study, two-sample *t*-test was used to compare the difference between the mean values of the corrections achieved with boundary conditions. The results of this comparison are shown in Table 5.

As can be seen from this table, there was a significant difference between the correction of both lumbar and thoracic curves in boundary conditions 1 and 3. Moreover, the *p*-value of the difference between the corrections of these curves in boundary conditions 1 and 3 was significant.

4. Discussion

There is no doubt that scoliosis curve, depending on the age of the subjects and severity of the curves, should be treated. Conservative treatment is one of the approaches used for this group of the subjects. Various types of braces have being used in this regard. However, the main question posted here is how we can improve the efficiency of the available braces. The efficiency of the available braces could be improved by a change in magnitude of the applied forces on the spine, direction of the forces and also by change in stabilization of spine (boundary conditions). The aim of this study was to evaluate the efficiency of use of various stabilization (boundary conditions) of spine on scoliotic curve correction.

A specific model of spine was developed based on CT scan images of a scoliotic subject. The results of validation check of the model and optimization method showed that the outputs of the model are accurate enough to determine the efficiency of various force and boundary conditions on spinal curve. There was no significant difference between the Cobb angle of lumbar and thoracic curves based on CT scan images and FEA software (the Cobb angles of lumbar and thoracic were 20 and 44, and 21 and 45 degrees based on CT scan images and FEA, respectively). The mechanical properties of spine (Young's modulus of elasticity and bone mineral density) of materials assigned on the model were in agreement with the available literature. Based on the results of various studies and scaling factor developed by Liu et al., Young's modulus of elasticity should be between 0.213 and 11.2 GPa and 0.117 and 0.2 GPa for bone and disk, respectively [3], which is in close agreement with the properties of the material assigned on this model, Table 2.

The results of this study showed that a change in boundary condition (end point control) influences the corrections achieved in both lumbar and thoracic parts. However, the interesting point was that the efficiency of lumbar fixation as boundary condition was greater than other conditions, especially when the combination of both transverse and vertical forces was applied on the spine. Therefore, it can be concluded that fixation of pelvic and applying the corrective forces on lumbar and thoracic curves does not provide too much correction compared to other conditions. It may be recommended to design a scoliotic brace to stabilize lumbar section which applies corrective forces in vertical and transverse directions. There was no study in literature regarding FEA analysis based on fixation criteria. However, the results of the study done by Liao et al showed that it is possible to remove the second strap of Boston brace, as force of this strap is negligible compared to the forces of other straps [16].

In clinical situation, various designs of the braces have been used to stabilize the scoliosis curve and to decrease the curve severity. In some braces, such as Milwaukee brace, the pelvis is fixed in both sides and the corrective forces applied mostly in transverse direction [15]. The same design has been used in the new design such as Lyon brace, asymmetrical rigid torsion brace and symmetrical patient oriented rigid three-dimensional active brace [7]. In these braces, a combination of both transverse and vertical directed forces have been used. In contrast, Cheneau and Cheneau light braces were designed to stabilize the pelvis on one side, and apply the forces in both vertical and transverse directions [22]. The results of studies available showed that the efficiency of Cheneau brace is more than that of the traditional braces, such as Milwaukee brace [8], [23]. The boundary condition used in this study was the same as those of available braces. The end point control in this study was the same as that of the available braces. The first type of boundary condition used in some designs, such as Lyon brace, ART (asymmetrical rigid torsion brace) and SPORT (symmetrical patient oriented rigid three dimensional active brace) [23]. The second type of boundary condition have been used in Cheneau and Cheneau light braces [23]. There are no specially designed braces that used the third type of boundary condition. The results of the current study showed that combination of both traction and transverse forces has more potential to correct scoliotic curve. However, it should be emphasized that in this study a double scoliotic curve with Cobb angle more than 40 degrees was used. In some braces, such as modified Boston brace, Lyon brace, ART (asymmetrical rigid torsion brace) and SPORT (symmetrical patient-oriented rigid three dimensional active brace), a combination of vertical and transverse force were used. Based on available literature, it can be stated that the efficiency of Boston, ART, and SPORT braces are more than that of Milwaukee brace [19]. Therefore, the results of the current studies are supported by the literature available. The interesting point regarding the results of this study was that an increase in efficiency of corrective forces was not associated with a significant increase in the magnitude of stress developed in spine structure, Table 4. This can be used in the new design of brace to produce new braces which offer both comfort and correction.

The main limitation of this study was that it was a case study. Moreover, only correction of the spine in frontal plane (scoliotic curve) was considered. It means that the changes in lordotic, kyphotic and rotation of the spine were not evaluated in this study. Therefore, the outputs of this study should be used with caution. It is recommended to do a study with more number of the subjects and with the same method.

5. Conclusion

The results of this case study showed that the location of boundary condition (end point control) influences the magnitude of the correction achieved with both transverse and vertical forces. Moreover, type of the forces (traction, transverse forces and combination of both) influence on curve correction. The results of this study can be used to design a new generation of the brace to be more effective. As this is a case study, the output of this study should be used with caution.

References

[1] AHN U.M., AHN N.U., NALLAMSHETTY L., BUCHOWSKI J.M., ROSE P.S., MILLER N.H., KOSTUIK J.P., SPONSELLER P.D., *The etiology of adolescent idiopathic scoliosis*, Am. J. Orthop. (Belle Mead NJ), 2002, 31, 387–395.

[2] BROX J.I., LANGE J.E., GUNDERSON R.B., STEEN H., 2012. *Good brace compliance reduced curve progression and surgical rates in patients with idiopathic scoliosis*, Eur. Spine J., 2012, 21, 1957–1963.

[3] BUCKLEY J.M., LOO K., MOTHERWAY J., *Comparison of quantitative computed tomography-based measures in predicting vertebral compressive strength*, Bone, 2007, 40, 767–774.

[4] CANAVESE F., KAELIN A., *Adolescent idiopathic scoliosis: Indications and efficacy of nonoperative treatment*, Indian Journal of Orthopaedics, 2011, 45, 7–14.

[5] CARR W.A., MOE J.H., WINTER R.B., LONSTEIN J.E., *Treatment of idiopathic scoliosis in the Milwaukee brace*, J. Bone Joint Surg. Am., 1980, 62, 599–612.

[6] DANIELSSON A., WIKLUND I., PEHRSSON K., NACHEMSON A., *Health-related quality of life in patients with adolescent idiopathic scoliosis: A matched follow up at least 20 years after treatment with brace or surgery*, Euro Spine J., 2001, 10.

[7] DE MAUROY J., *The new Lyon ARTbrace: Asymetrical rigid Torsional Brace*.

[8] DEIMLING U., WAGNER U.A., SCHMITT O., *Long-term effect of brace treatment on spinal decompensation in idiopathic scoliosis: a comparison of Milwaukee brace – Cheneau corset* [in German], Z. Orthop. Ihre Grenzgeb., 1995, 133.

[9] GANJAVIAN M.S., BEHTASH H., AMERI E., KHAKINAHAD M., *Results of Milwaukee and Boston braces with or without metal marker around pads in patients with idiopathic scoliosis*, Acta Med. Iran, 2011, 49, 598–605.

[10] GIGNAC D., AUBIN C.E., DANSEREAU J., LABELLE H., *Optimization method for 3D bracing correction of scoliosis using a finite element model*, Eur. Spine J., 2000, 9, 185–190.

[11] GOLDBERG C.J., MOORE D.P., FOGARTY E.E., DOWLING F.E., *Scoliosis: a review*, Pediatric Surgery International, 2008, 24, 129–144.

[12] HSU J.D., MICHAEL J.W., FISK J.R., *AAOS atlas of orthoses and assistive devices*, 4th ed., American Academy of Orthopaedic Surgeons, Philadelphia: Mosby/Elsevier, 2008.

[13] JANICKI J.A., ALMAN B., *Scoliosis: Review of diagnosis and treatment*, Paediatrics & Child Health, 2007, 12, 771–776.

[14] KARIMI M.T., EBRAHIMI M.H., MOHAMMADI A., MCGARRY A., *Evaluation of the influences of various force magnitudes and configurations on scoliotic curve correction using finite element analysis*, Australasian Physical and Engineering Sciences in Medicine, 2016, 1–6.

[15] KARIMI M.T., RABCZUK T., *Scoliosis conservative treatment: A review of literature*, Journal of Craniovertebral Junction & Spine, 2018, 9, 3–8.

[16] LIAO Y.C., FENG C.K., TSAI M.W., CHEN C.S., CHENG C.K., OU Y.C., *Shape modification of the Boston brace using a finite-element method with topology optimization*, Spine (Phila Pa 1976), 2007, 32, 3014–9.

[17] MEIJER G.J.M., *Development of a Non-Fusion Scoliosis Correction Device: Numerical Modelling of Scoliosis Correction.* PhD, University of Twente, 2011.

[18] NATARAJAN R.N., WILLIAMS J.R., ANDERSSON G.B., *Recent advances in analytical modeling of lumbar disc degeneration*, Spine (Phila Pa 1976), 2004, 29, 2733–41.

[19] NEGRINI S., DONZELLI S., AULISA A.G., CZAPROWSKI D., SCHREIBER S., DE MAUROY J.C., DIERS H., GRIVAS T.B., KNOTT P., KOTWICKI T., LEBEL A., MARTI C., MARUYAMA T., O'BRIEN J., PRICE N., PARENT E., RIGO M., ROMANO M., STIKELEATHER L., WYNNE J., ZAINA F., *2016 SOSORT guidelines: orthopaedic and rehabilitation treatment of idiopathic scoliosis during growth*, Scoliosis and Spinal Disorders, 2018, 13, 3.

[20] PERIE D., AUBIN C.E., PETIT Y., BEAUSEJOUR M., DANSEREAU J., LABELLE H., *Boston brace correction in idiopathic scoliosis: a biomechanical study*, Spine (Phila Pa 1976), 2003, 28, 1672–1677.

[21] PERIE D., AUBIN C.E., PETIT Y., LABELLE H., DANSEREAU J., *Personalized biomechanical simulations of orthotic treatment in idiopathic scoliosis*, Clin. Biomech. (Bristol, Avon), 2004, 19, 190–5.

[22] PERIE D., SALES DE GAUZY J., HOBATHO M.C., *Biomechanical evaluation of Cheneau-Toulouse-Munster brace in the treatment of scoliosis using optimisation approach and finite element method*, Med. Biol. Eng. Comput., 2002, 40, 296–301.

[23] KARIMI M.T., RABCZUK T., KAVYANI M., *Evaluation of the efficiency of the Cheneau brace on scoliosis deformity : A systematic review of the literature*, Orthopade, 2018, 47, 198–204.

[24] VASILIADIS E., GRIVAS T.B., SAVVIDOU O., TRIANTAFYLLOPOULOS G., *The influence of brace on quality of life of adolescents with idiopathic scoliosis*, Stud. Health Technol. Inform., 2006, 123.

[25] WALLS M.C., RAJAGOPALAN S., 2013. Chapter 14 – *Computed Tomographic Angiography*, A2 – Creager M.A. [in:] J.A. Beckman, J. Loscalzo (Eds.), *Vascular Medicine: A Companion to Braunwald's Heart Disease (Second Edition)*, W.B. Saunders, Philadelphia 2013.

[26] WANG L., ZHANG B., CHEN S., LU X., LI Z.Y., GUO Q., *A Validated Finite Element Analysis of Facet Joint Stress in Degenerative Lumbar Scoliosis*, World Neurosurg., 2016, 95, 126–133.

[27] WANG W., BARAN G.R., BETZ R.R., SAMDANI A.F., PAHYS J.M., CAHILL P.J., *The Use of Finite Element Models to Assist Understanding and Treatment For Scoliosis: A Review Paper*, Spine Deformity, 2014, 2, 10–27.

[28] WEINSTEIN S.L., *Idiopathic scoliosis in adolescence. Incidence and progression of untreated scoliosis*, Orthopade, 1989, 18, 74–86.