



Original article

Optimizing the vertical position of the brace thoracic pad: Apical rib or apical vertebra?

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ABSTRACT

Introduction: The vertical position of the thoracic pad is a subject of controversy in brace design. Traditional recommendations dictate a maximal force applied at the level of the apical rib, about 2 levels below the apical vertebra. We sought to evaluate the optimal vertical position of the brace thoracic pad using fulcrum bending radiographs.

Hypothesis: A lateral force applied at the apical vertebra of a thoracic curve is more efficient at correcting coronal deformity than a force placed the apical rib.

Patients and methods: In this prospective study, we recruited patients presenting with adolescent idiopathic scoliosis (AIS) and Risser stage 0–2 over a period of 12 months. Patients with a history of spine or thoracic surgery were excluded. Two fulcrum bending radiographs were performed for each patient: one with the center of the fulcrum placed under the most lateral part of the apical rib and another with the fulcrum centered below the apical vertebra. Cobb angles were measured on each fulcrum radiograph and compared using a paired t test.

Results: Fifty-two patients were included, with a mean age of 12.4 years and mean thoracic Cobb angle of 39.4°. Placing a fulcrum under the apical vertebra reduced the Cobb angle to a mean of 11.5°, which was significantly lower than a fulcrum placed under the apical rib (14.3°, $p = 0.001$). This corresponded to a 20% relative loss in the absolute correction angle when placing the fulcrum under the apical rib. The difference between the 2 Cobb angles was not significantly correlated to patient age ($p = 0.896$) or curve apex ($p = 0.813$).

Discussion: This is the first clinical study addressing the vertical position of the thoracic pad in braces for AIS. A lateral force applied at the level of the apical vertebra was significantly more efficient at reducing thoracic curve deformities than one applied at the apical rib. Our results provide clinical support to finite element studies that refute traditional recommendations of brace design, advocating for a revision of these guidelines to optimize non-operative treatment of AIS.

Level of evidence: II, prospective comparative study.

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1. Introduction

Bracing represents the mainstay of non-operative treatment in adolescent idiopathic scoliosis (AIS). Despite substantial progress in materials and design, many uncertainties still reign upon the exact mechanism of action and optimal design features of a brace [1,2]. One of the most commonly accepted concepts in brace biomechanics is the three loading point principle, which comprises a main force applied at the curve apex on the convex side accompanied

by two counter-forces applied on the concave side [3]. These are located at the axillary and lumbar levels in the case of a thoracic curve. Applying an apical force on the spine at the thoracic level is quite challenging due to the presence of the rib cage. Indeed, ribs have a descending anatomical course making the rib apex more caudad compared to the vertebral apex. Moreover, the mechanical transmission of forces between the rib cage and the thoracic spine is still not fully appreciated [4].

Traditional recommendations of brace design dictate a maximal force applied at the level of the rib corresponding to the curve apex [5–9]. However, there is no strong evidence to support these recommendations, and several modeling studies have found conflicting results when trying to address that issue [10–12].

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The International Society on Scoliosis Orthopaedic and Rehabilitation Treatment (SOSORT) conducted a survey among scoliosis specialists on the biomechanical actions of braces and the selection of force vectors for optimal curve correction [13]. The results showed a clear disparity in expert opinion on the vertical position of the thoracic pad: almost half of the experts supported a force applied at the level of the apical rib, while the other half preferred a more cephalad vector, located at the level of the apical vertebra.

Fulcrum-bending radiographs were introduced by Cheung and Luk were presented as a better alternative to traditional supine bending radiographs [14]. Their primary purpose is to evaluate the flexibility of the deformity and assist in pre-operative planning. The technique was validated by several subsequent studies that confirmed its reliability in evaluating scoliotic curve reducibility, predicting postoperative reduction and selecting appropriate fusion levels [15–20]. Fulcrum bending radiographs thus represent a reliable and reproducible tool that can be used to simulate a passive lateral pressure force applied inside a brace. We conducted a clinical study to evaluate the optimal vertical position of the apical force exerted by the thoracic pad inside a brace using fulcrum bending radiographs. Our study hypothesis was that a lateral force applied at the apical vertebra of a thoracic curve is more efficient at correcting coronal deformity than a force placed the apical rib.

2. Patients and methods

2.1. Patients

Subjects were recruited among new patients presenting to our scoliosis clinic over a period of 12 months and getting diagnosed with AIS. The study was approved by our institutional ethics committee and is in compliance with the Declaration of Helsinki. Informed, written consent was obtained for participation in the study. Inclusion criteria comprised: age 10 years or older, Risser stage 0–2, thoracic curve with apex from T6 to T12 and a Cobb angle of 20 to 50 degrees on anteroposterior radiographs. The curve angle inclusion range used is wider than that recommended by Richards et al. as standardized inclusion criteria for brace studies (25 to 40 degrees); however this present study is not a brace outcome study per se [21]. Exclusion criteria included non-idiopathic scoliosis and history of spinal or thoracic surgery. Patients were classified according to the Lenke classification [22]. The apex of the structural main thoracic curve was selected for analysis in all but type 5 curves, where T12 was the apex studied, as the main thoracic curve is non-structural in this type.

2.2. Methods

Standard standing anteroposterior radiographs were used to determine the level of the apex and measure the frontal Cobb angle in neutral position. Two fulcrum bending radiographs were performed for each patient: one with the center of the fulcrum placed under the most lateral part of the apical rib and one with the center of the fulcrum placed at the level of the apical vertebra. The first radiograph actually corresponds to the one described by Cheung and Luk for thoracic curves and was performed with some adjustments to their original description [14]. In order to locate the apical rib, those authors determined the apical level on standard standing anteroposterior X-rays, then clinically identified the 12th rib on the patient (last palpable rib) and counted ribs from caudad to cephalad. Since exact positioning of the fulcrum was critical in our study, we preferred to resort to fluoroscopic guidance to ascertain proper localization of the apical rib or apical vertebra. After localizing the proper level according to clinical palpation as described, a paperclip was placed on the patient's back using paper tape and proper positioning was confirmed via fluoroscopy and adjusted as needed. The 'Low Dose' option was used when using fluoroscopy. All radiographs were performed by the same X-ray technician and in the presence of one of the study investigators to verify adequate positioning. After using a cylindrical fulcrum for the first 4 months of the study, we designed a prismatic one to ensure a more focused application of the vector force (Fig. 1). Similarly, in a recent technical note, Cheung et al. reported modifying their initial cylindrical design to a prism-shaped fulcrum [23]. The rationale for their modification was difficulty with patient positioning due to rolling of the cylindrical fulcrum and the need for multiple different-sized cylindrical fulcrums, which can be obviated by using a single triangular fulcrum with different lengths for each side [22].

2.3. Methods of assessment

Our major outcome consisted of the difference between frontal Cobb angles measured on the 2 fulcrum bending X-rays for each patient (Fig. 2). Indeed, the Cobb angle is an objective parameter widely used to quantify the severity of the scoliotic deformity, follow its progression with time and evaluate its reducibility [23–26].

2.4. Statistical analysis

Statistical calculations were done using SPSS 16.0 (SPSS Inc., Chicago IL). A paired t-test was used to compare Cobb angles with the fulcrum under the apical rib vs. apical vertebra. An unpaired t-test was used to compare Cobb angles in either position between the 2 different fulcrum designs. Correlation between the difference in absolute curve reduction and patient age was tested using

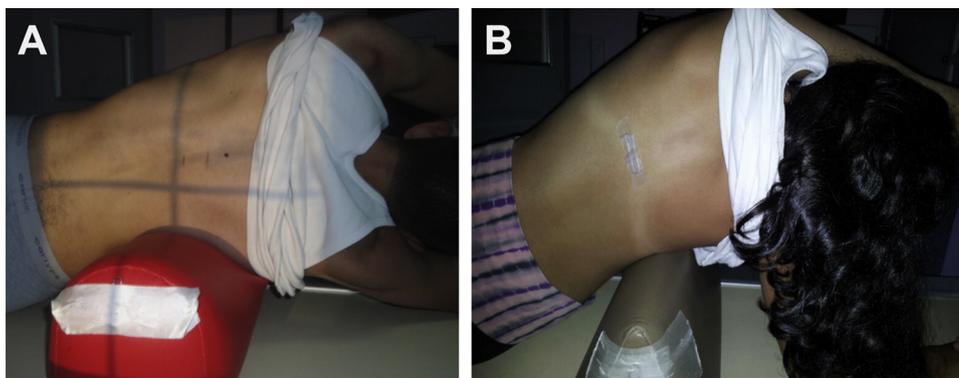


Fig. 1. Fulcrum bending radiographs being taken with use of a cylindrical fulcrum (A) and a prismatic fulcrum (B).

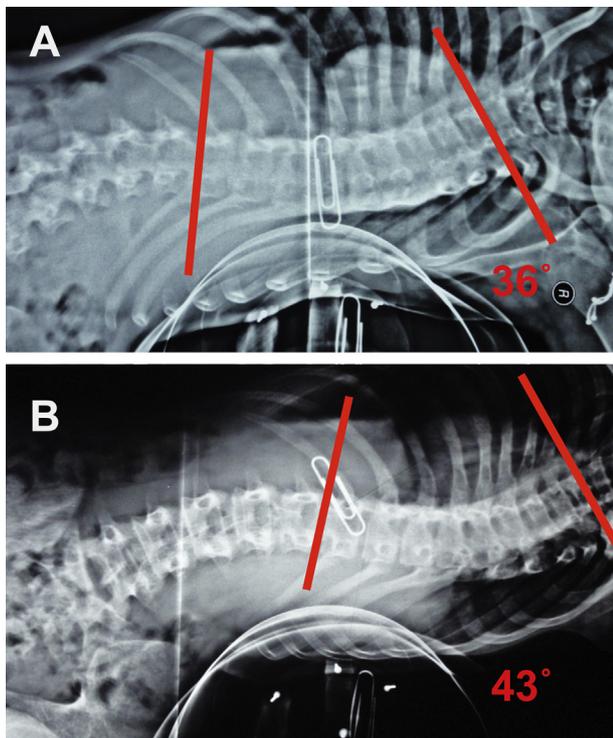


Fig. 2. Fulcrum bending radiographs in an eleven-year-old female with adolescent idiopathic scoliosis with thoracic curve apex at T8. A. Fulcrum placed under the apical vertebra (cobb angle 36°). B. Fulcrum placed at the level of the apical rib (cobb angle 43°).

Pearson's correlation coefficient. ANOVA was used to analyze the relationship between the difference in absolute curve reduction and curve apex or Lenke type. A sample size analysis with a type I error of 0.05 and a standard deviation of 9° (highest group variability noted in Cheung et al.'s series [15]) had revealed the need for a minimum of 13 patients for an effect difference of 5° and 35 patients for an effect difference of 3°.

3. Results

Fifty-two patients (41 female and 11 male) met the inclusion criteria and consented to participate in this study. The mean (\pm standard deviation) age was 12.4 (\pm 1.4) years and curve apices varied from T6 to T12 along a distribution represented Table 1. The mean (\pm standard deviation) Cobb angle on standing antero-posterior radiographs taken in neutral position was 39.4 (\pm 11.3) degrees. The mean Cobb angle with the fulcrum placed under the apical rib was 14.3 degrees, which was significantly higher than the mean Cobb angle with the fulcrum placed under the apical vertebra: 11.5 degrees ($p=0.001$). The mean difference of 2.8 degrees corresponds to a 19.6% reduction in the absolute correction angle when placing the fulcrum under the apical vertebra instead of the apical rib. There was an 11.1% relative gain in the correction rate, from 63.7% with the fulcrum placed under the apical rib to a 70.8% correction rate with the fulcrum placed under the apical vertebra. The difference remained statistically significant after excluding the 11 patients with an apex at the level of the floating ribs T11 and T12 ($p=0.002$), and averaged 3.3 degrees.

The difference between the 2 Cobb angles was not related to patient age ($p=0.896$) or curve apex ($p=0.813$). Table 1 details the distribution of curve apices and the Cobb angle measurements for each apical level. The distribution of curve types according to the Lenke classification is reported in Table 2. When isolating only the 34 type 1 curves in the analysis (main thoracic curves), the mean

Cobb angle with the fulcrum under the apical rib was 16.0 degrees and the angle with the fulcrum under the apical vertebra was 12.5 degrees ($p=0.004$). Furthermore, the mean difference in absolute curve reduction between the 2 positions of the fulcrum was not found to be statistically different among the different Lenke type groups ($p=0.266$).

When looking at the cylindrical fulcrum and the prismatic fulcrum separately, each group yielded statistically significant results when comparing the 2 different positions of the fulcrum: mean difference of 2.4 degrees with the cylindrical fulcrum ($p=0.014$) and 3.1 degrees with the prismatic fulcrum ($p=0.022$). When comparing the Cobb angle between the 2 fulcrum shapes, no statistically significant difference was found in either of the fulcrum positions ($p=0.516$ for the fulcrum placed under the apical rib, and $p=0.615$ for the fulcrum placed under the apical vertebra).

4. Discussion

The results obtained confirmed our hypothesis that a lateral force applied at the apical vertebra of a thoracic curve is more efficient at correcting coronal deformity than a force placed the apical rib. Traditionally, braces destined to treat thoracic scoliosis are designed to have a main corrective force at the level of the apical rib, sometimes even lower [3,5–9]. However, after reviewing the available literature, we were unable to identify any strong evidence to support this practice. Looking to shed more light into this issue, as well as into other biomechanical properties of brace design, several studies relying on mathematical models have sought the optimal brace features for maximal correction of scoliotic deformities. Andriacchi et al. conducted a study on 5 computer-reconstructed spine models on which they simulated the effect of a Milwaukee brace [10]. For a thoracic curve with an apex at T10, maximal reduction was obtained with a thoracic pad placed at the 7th to 10th ribs, thus contradicting traditional recommendations [3,5–9]. Placing the pad 2 segments below led to a 25% loss in correction, which is consistent with the extent of loss in reduction observed in our study with the fulcrum placed under the apical rib. Gignac et al. compared the magnitude, direction in the horizontal plane and vertical position of anterior and posterior corrective thoracic forces [11]. They used 20 different models with thoracic apices between T8 and T9. Their results showed that, in the absence of a lumbar counter-force, the optimal direction of the corrective thoracic force is posterolateral and should be applied at the 9th rib for optimal reduction, which corresponds to traditional recommendations. However, with the presence of a lumbar vector force, which is usually the case in thoraco-lumbo-sacral orthoses, the optimal vertical position shifts to the 5th rib, a much higher level. A more recent study by the same team explored the effect of 15 brace design features on 3 patient models obtained by three-dimensional reconstruction [12]. This study showed that changing the position of the upper limit of the thoracic pad from the apical rib to 2 ribs above did not have any significant effect on the frontal Cobb angle, which led the authors to reject traditional recommendations used by orthotists. Moreover, when taking a closer look at their results, the patient model with a major thoracic curve witnessed a decrease in the frontal Cobb angle when placing the upper limit of the thoracic pad at a higher level, without however reaching statistical significance [12].

Despite these modeling studies that refute the widely accepted recommendations for brace design, a clinical study is essential to initiate any movement towards revising traditional guidelines. Fulcrum bending radiographs came to our mind as an appropriate tool to clinically evaluate the reducibility of thoracic curves with different vertical positions of a lateral corrective force. We used the passive reaction force exerted by the fulcrum to simulate a lateral pressure force applied by the thoracic pad in a brace. We did not

Table 1
Distribution of findings based on Lenke classification of curve type.

Lenke type	Number of patients (%)	Mean apical rib Cobb angle (degrees)	Mean apical vertebra Cobb angle (degrees)	Mean difference (degrees)	p-value
1	34 (65.4%)	16.0	12.5	3.5	0.266
3	8 (15.4%)	13.1	12.7	0.4	
5	8 (15.4%)	8.4	7.4	1.0	
6	2 (3.8%)	14.0	6.0	8.0	

Table 2
Distribution of findings based on apical level.

Apex	Number of patients	Mean apical rib Cobb angle (degrees)	Mean apical vertebra Cobb angle (degrees)	Mean difference (degrees)	p-value
T6	2	36.0	35.0	1.0	0.813
T7	5	16.0	11.6	4.4	
T8	19	13.4	9.9	3.5	
T9	12	13.1	10.8	2.3	
T10	3	18.3	12.0	6.3	
T11	3	19.0	18.7	0.3	
T12	8	8.4	7.4	1.0	

detect any difference in the magnitude of curve correction with the prismatic fulcrum as compared to the cylindrical fulcrum. As stated in the recent paper by Cheung et al., we did find the triangular fulcrum easier for positioning [22]. We found a clear superiority of a lateral force applied at the level of the apical vertebra compared to one applied at the apical rib in correcting thoracic scoliotic curves. This represents a clinical support to the conclusions of the aforementioned modeling studies and advocates for the revision of traditional recommendations for brace design.

Furthermore, the results of this study may suggest a more transverse transmission of forces from the rib cage to the thoracic spine, as opposed to a force transmission that follows the anatomic course of the ribs. Indeed, force transmission between the rib cage and the spine is not fully understood and many have attempted to further elucidate it [4,27,28]. The ribs, sternum, costo-vertebral joints and soft tissues of the chest wall including intercostal muscles significantly contribute to the stiffness and stability of the thoracic spine. Watkins et al. evaluated 10 C7-L1 cadaver specimens and found that the rib cage increased thoracic spine stability by 35% in lateral bending and 31% in axial rotation [27]. In a later study on 4-level-segment specimens of the thoracic spine, Brasiliense et al. found even higher contribution of the rib cage to thoracic stability, with a 182% increase in lateral bending and 948% increase in axial rotation of the thoracic spine after removal of the rib cage [28]. Both these studies however evaluated forces exerted on the spine at both ends of the specimens, as opposed to forces exerted peripherally on the rib cage, such as is the case with bracing. Moreover, there often exists a deformity of variable severity in the ribs and chest in patients with AIS, which may alter the biomechanical relationship between the spine and the rib cage [3]. Further research on force transmission from the chest wall to the thoracic spine, especially in patients with AIS, is thus warranted.

Our study included several limitations. We included 8 subjects with thoraco-lumbar scoliosis with a T12 apex. Including these subjects led to a heterogeneous population because throaco-lumbar curves represent a separate entity that may have a different biomechanical behavior. However, even after excluding subjects with an apex at the level of the floating ribs (T11 and T12), the results remained statistically significant. The observed mean difference of 2.8 degrees may appear as clinically insignificant, especially in the face of reported inter-observer reliability of Cobb angle measurement of 4 degrees, with some studies reporting variability of up to 8 degrees, and a recommended threshold of 5 degrees when assessing significant curve progression [21,29,30]. However, these values are based on non-corrected neutral curves, whereas the difference reported here represents a difference in bending corrected curves, and corresponds to a 20% loss in absolute correction

angles when placing the fulcrum under the apical rib. Furthermore, it did reach statistical significance. Moreover, our primary intent in using fulcrum bending radiographs was to simulate the major apical force applied by the brace thoracic pad. However, the fulcrum and the thoracic pad do not have exactly the same shape, and the force exerted by the fulcrum is strictly lateral, has a magnitude that depends on the patient's body weight and is the only external pressure force being applied on the patient's chest when the radiograph is taken. On the other hand, the pressure exerted by the thoracic pad is usually posterolateral, its magnitude mostly depends on strap tension, and it is accompanied by a multitude of other forces simultaneously exerted inside the brace [31–34]. These passive and active forces inside a brace contribute to a three-dimensional derotation of the scoliotic deformity, which is clearly not reproduced by the sole passive lateral force exerted by the fulcrum. Lastly, in-brace films were not analyzed in this study, and ideally in-brace imaging with different positions of the thoracic pad within the brace would ultimately provide more reliable evidence for this issue and should be considered for future research.

In conclusion, our study represents the first clinical study that addresses the issue of the vertical position of the thoracic pad in braces destined to manage thoracic curves in patients with AIS. A lateral force applied at the level of the apical vertebra was significantly more efficient than a force applied at the level of the apical rib in reducing thoracic curve deformities in our series. This corroborates prior modeling studies, and contradicts traditional recommendations for brace design, which advise placing the thoracic pad at the level of the apical rib or even below. Thus, we advocate revisiting current standards of brace design to provide optimal correction of thoracic curves in patients with AIS. Additional clinical studies, including true bracing studies comparing the outcome of different brace designs, should be considered to further solidify our findings.

Disclosure of interest

Joseph Karam, Roy Eid, Gaby Kreichati, Rami Abiad, Khalil Kharat and Ismat Ghanem declare that they have no competing interest.

Ethical approval

This work was approved by the institutional ethics committee, and is in compliance with the ethical standards of the national research committee and with the 1964 Helsinki declaration and its later amendments.

Informed consent

Informed consent was obtained from the parents and patients for all individual participants included in the study.

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Authors' contribution

Substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work: J.K., R.E., K.K., G.K., R.A., I.G.

Drafting the work or revising it critically for important intellectual content: J.K., R.E., K.K., G.K., R.A., I.G.

Final approval of the version to be published: J.K., R.E., K.K., G.K., R.A., I.G.

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