Effectiveness and biomechanics of spinal orthoses in the treatment of adolescent idiopathic scoliosis (AIS)


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Abstract
In this prospective study, the effectiveness and biomechanical factors of spinal orthoses in the treatment of moderate adolescent idiopathic scoliosis (AIS) patients were investigated. In the first 20 months of orthotic treatment, the values of standing AP Cobb's angle, apical vertebral rotation, lumbar lordosis as well as thoracic kyphosis showed significant reduction (P<0.05), however, the angle of trunk inclination and trunk listing did not. The values of those reducible parameters reached their lowest values within the first 12 months of orthotic treatment and then the values gradually increased but they were still below the pre-brace values. The mean pressure of the pressure pads was found to be 7.09±1.77kPa (53.2±13.3mmHg) while the mean tension of the straps was 26.8±5.2N. The standing AP Cobb's angle strongly correlated with the pad pressure (correlation coefficient=0.931, p<0.05) and strap tension (correlation coefficient=0.914, p<0.05). The strap tension and pad pressure strongly correlated and the correlation coefficient was 0.873 (p<0.05). This suggests that in the consideration of biomechanical function of spinal orthoses, the focus may be upon how tightly the orthosis was fastened and if the location and direction of the pressure pads are correct. Therefore, for enhancing the effectiveness of orthotic treatment, an independent standard tension should be set in each strap, and regular and close monitoring is needed.

Introduction
The conventional spinal orthoses have been demonstrated to be effective in altering the natural history of adolescent idiopathic scoliosis (AIS) (Nachemson and Peterson, 1995; Emans et al., 1986; Winter et al., 1986; Carr et al., 1980) and their effectiveness varies from 72% to 89% of the cases being treated. The differences are due to the variations in curve pattern and severity, treatment technique and protocol and the period of study. In a prospective study of AIS with right thoracic curves between 25° and 35°, Nachemson and Peterson (1995) found that orthotic treatment was successful in preventing curve progression of more than 6°. It was suggested that spinal orthoses should be prescribed to AIS patients with curves between 30° and 40°, or with progressive curves more than 25° (Nachemson and Peterson, 1995; Lonstein and Winter, 1994; Edgar, 1985; Kehl and Morrissy, 1988; Nash and Ohio, 1980). Obviously, for those scoliotic curves which are not likely to progress, the orthosis cannot be claimed effective. Ogilvie (1994) commented that thoraco-lumbo-sacral orthosis (TLSO) was the most common non-operative treatment in progressive AIS Nachemson and Peterson (1995) postulated that orthotic treatment was to modify bio-mechanically the morphology of the scoliotic spine and to control the progression of the spinal curvature through applying pressures...
to the trunk over a prolonged period.

Regarding the forces generated by orthoses on the scoliotic deformities, Chase et al. (1989) measured forces exerted in situ by the orthosis and found that curves correction was not solely dependent on the magnitude of force applied by the orthosis. For large curves, they commented, that correction might be little despite the large magnitude of the forces applied. Cote et al. (1992) developed a flexible matrix composed of thin circular pressure sensors for measuring the entire skin-orthosis interface pressures. It was suggested that the action forces of Boston orthoses were limited mainly to specific regions.

From the previous studies, little was known about the correlation of the biomechanical parameters (pad pressures and strap tensions) with the major deformities such as Cobb’s angle and the apical vertebral rotation. The current study focused upon a prospective evaluation of the clinical effectiveness and biomechanics of spinal orthoses in the treatment of moderate AIS. For the evaluation of such effectiveness, both radiographic and anthropometric outcome measures were used. It was hypothesised that the application of spinal orthoses in the treatment of moderate AIS would contribute to the reduction of the spinal deformities in the three anatomical planes. It was believed that the mechanism of control of deformities might come from the persistent application of external forces that would cause time-dependent changes in the soft tissues. Therefore, in this study the interfacial pressures under the different pressure pads and the tensions of the different straps of the spinal orthoses were studied over a period of time to investigate the temporal changes in these biomechanical factors.

Materials and methods

Patient selection criteria

The patient selection criteria were – a) Female patients with progressive AIS; b) Cobb’s angle: 25°-45°; c) age: 10-14 years; d) Risser sign ≤3; and e) newly treated with thoraco-lumbo-sacral orthosis (TLSO).

Patients and their maturity

Thirty-three (33) female patients were selected according to the set criteria. Before completing the data collection period, 3 defaulted and 4 underwent surgical treatment due to curve deterioration. The full data set obtained from the remaining 26 patients were analysed. The patient’s maturity was measured in terms of chronological age mean (mean=12.9 years, SD=1.4, range=10-15), bone age (mean=13.2 years, SD=0.9, range=11-15.5) (Greulich and Pyle, 1959) and Risser sign (mean=1.5, SD=1.2, range=0-3) (Risser, 1958). The mean value of the menarche was 12.5 years (SD=1.0, range=10.5-14.8).

Parameters and methods of measurements

In this study, both radiographic and anthropometric measurements were taken as the clinical assessment parameters to evaluate the efficacy of the orthoses. They were as follows:

- the AP Cobb’s angles measured using Cobb’s method from standing antero-posterior radiographs. The Cobb’s method was also used in the measurements of sagittal curvatures including thoracic kyphosis and lumbar lordosis from standing lateral radiographs (Cobb, 1948);
- the apical vertebral rotations measured using Perdriolle’s method from standing A-P radiographs (Perdriolle, 1985);
- the trunk listing measured using plumbline method (Rudicel and Renshaw, 1983);
- the angle of trunk inclination measured using Scoliometer (Bunnell, 1984; Tachdjian, 1990).

For the biomechanical measurement, electro-hydraulic sensors were used for the measurements of interfacial pressures between the body and the axillary pad, thoracic pad, lumbar pad and pelvic pad while purpose-designed buckle force-transducers were used for tension measurements of the axillary strap, thoracic strap, lumbar strap and pelvic strap. The details of measurements are described in the following sections.

Measurements of strap tension

The purpose-designed buckle force-transducer (Fig. 1) used to measure the strap tension was small 35x35x5mm). The tension on the strap could be measured in situ without modification to the brace or strap. It was simple to install – by taking out the removable pin and placing the transducer on the strap then re-inserting the pin to the original position.

With the buckle force-transducer placed on the strap, the tensile force along the strap generated bending moments in the two
Fig. 1. The structure and force diagram of the purpose-designed buckle force transducer.

longitudinal beams. As these beams were subject to three-point bending, the highest stresses were generated to the central pin. The relationship between the tensile strap force and the amount of moment generated depended on the offset from the longitudinal axis of the strap (Fig. 1). The amount of moment that deformed the central beam was sensed by two strain gauges. The three metal rods of the buckle transducer formed the axis for thin nylon rollers, which helped to reduce friction between the strap and the metal rod. Another purpose of the nylon rollers was to increase the amount of strap offset which would accordingly increase the sensitivity of the transducer without greatly changing the strap length. The transducer was connected as a half-bridge system with two strain gauges, one attached to either side of one of the beams. The strain gauges of the buckle force-transducer were manufactured by Tokyo Sokki Kenkyujo Co., Ltd. and their specifications were - type: FLA-3-23, gauge length: 3mm, gauge resistance: 120±0.3Ω and gauge factor (strain-sensitivity factor): 2.15.

The output of the buckle force transducer was calibrated using Hounsfield Testing Equipment (Model H10KM) (Hounsfield Testing Equipment Ltd., England) and a Strain Indicator (Model P-3500) (Vishay Measurements Group, USA). The buckle force-transducer was placed on double-layer Dacron straps. The two ends of the strap were firmly anchored via special grips to the load cell (to simulate the condition as in the spinal orthosis). The strap was loaded in tension from 0 to 300N (normal strap tension estimated to be less than 200N) and then unloaded. The loading and unloading rate was 10mm/min. Initially significant hysteresis was observed which might be due to the visco-elastic properties of the Dacron strap, and the friction between the strap and buckle transducer. These adverse factors have been minimised by preconditioning the Dacron strap, using concentric nylon rollers and increasing the buckle frame rigidity. After the above improvements, the degree of hysteresis was reduced and the measurement accuracy for the strap tension was ±1N (Wong and Evans, 1998).

Measurement and interfacial pressure
The interfacial pressure between the patient's body and the different pressure pads was measured by a Dynamic Pressure Monitor.
(DPM, Model 2000C) (Raymar Ltd., England). It was an electro-hydraulic system, which operated at a sampling rate of 1Hz for all sensors. The sampling rate was required in view of the effects of breathing. The measurement range was from 0 to 32kPa (0 to 240mmHg).

The Dynamic Pressure Monitor had two measuring matrices (each covering a total area of 2,700mm$^2$) and each had four circular electro-hydraulic sensors (each with a diameter of 14mm) that were arranged in a parallelogram shape (Fig. 2). The matrices were held in place with adhesive tape on the inner surface of the pressure pads for measuring the interfacial pressure. A Macintosh computer was required to run the software of the DPM 2000C.

In calibrating the Dynamic Pressure Monitor, four pieces of equipment were used. They were a plastic airbag, a calibration chamber, a sphygmomanometer and a hand pump. In the calibration process, the pressure sensors were sandwiched within the airbag (Fig. 2) and were placed in the calibration chamber which was a rectangular wooden box with an opening at one end. The pressure of the airbag was increased from 0 to 32kPa (0 to 240mmHg) using a hand pump and the magnitude of pressure was recorded by the DPM. The pressure of the airbag was also measured by the sphygmomanometer. The accuracy of the DPM could be obtained by comparing the reading of DPM with that of the sphygmomanometer. Adjustments of the potentiometers were sometimes necessary in order to achieve reliable measurements. For the current study, the measuring range was between 2.67 and 20kPa (20 and 150mmHg), the accuracy ±0.27kPa (± 2mmHg). Moreover, zeroing process was performed for each sensor by the system before each measurement, as the electro-hydraulic sensors were located at different heights on the inner surfaces of the spinal orthosis.

A complementary study was carried out on 3 patients for testing the repeatability of biomechanical measurements. Measurements were repeated three times for each patient. It was found that the standard deviations for the strap tension of the four straps and of the pad pressure for 3 patients were ≤2.6N and 0.53kPa (4mmHg) respectively.

![Fig. 2. The hydraulic pressure sensors were sandwiched within the inflatable plastic bag then inserted in the calibration chamber prior to calibration.](image-url)
Procedures of measurement

The period of data collection was 36 months started from June 1995. Subjects were referred from the Scoliosis Clinic of the Duchess of Kent Children's Hospital, Sandy Bay, Hong Kong. The treating orthotist would put markings on the straps after he had tightened the straps to a desirable tension (based on his experience) before taking X-rays. The patient was instructed to tighten the straps to the updated markings.

At the first visit of each subject, the clinical, radiographic (antero-posterior and lateral views) and anthropometric measurements were taken. At the second visit, a spinal orthosis was delivered to the subject, and the radiographic, anthropometric and biomechanical measurements were taken. Subsequently, all measurements were taken at every follow-up clinic at 4-month intervals till the 20th month of orthotic application. The pressures acting on the axillary pad, thoracic pad, lumbar pad and pelvic pad, and the tensions of the axillary strap, thoracic strap, lumbar strap and pelvic strap were measured with the patient in-brace standing during normal and deep breathing activities at each follow-up clinic. A schematic diagram for illustrating the locations of the built-in pressure pads and their corresponding straps, and the process of measurements are shown in Figures 3 and 4 respectively.

Before each measurement, the patients' orthoses were fastened to their updated markings determined by their treating orthotist. The DPM and buckle transducers were calibrated. The measurements of the pad pressures and strap tensions were recorded simultaneously over 30 seconds. Before the formal measurements the two systems were synchronised by simply asking the subject to hold her breath for 5 seconds, and the measured values of the two systems were quite steady during that period.

A breathing cycle normally took 5 seconds. Therefore 5 to 6 breathing cycles were recorded during the 30-second period of actual measurement. The sampling rate of the DPM was 1Hz and 30 samples were measured, while the strap tensions were measured continuously for 30 seconds. The subjects were requested to stand and perform normal breathing for 30 seconds and then deep breathing for another 30 seconds. There were 2 sensing matrices of the DPM and 2 buckle force-transducers as only 2 channels were available in the XYt-recorder.

With the limitation of the equipment, it was not possible to measure simultaneously the interfacial pressures of the 4 pads (axillary pad, thoracic pad, lumbar pad and pelvic pad) and the tensions of the 4 straps (axillary strap, thoracic strap, lumbar strap and pelvic strap). Therefore, in the measuring protocol, the 2 pressure matrices were first attached to the axillary pad and thoracic pad, and the 2 buckle transducers were first placed on the axillary strap and thoracic strap. Measurements in the other two pads and straps were performed by repeating the process. Small reference holes were drilled in the orthoses to mark the location of the matrices to allow interfacial pressure measurements to be made on the same areas at subsequent visits.

Results

The data were analysed using the Statistical Package for Social Sciences (SPSS) (Version 9.0). A general linear model with within-subjects analysis was used. Repeated measures of analysis of variance (ANOVA) were applied to compare the mean differences for the studied parameters at the pre-brace visit and at the five

Fig. 3. Locations of the built-in pressure pads and their corresponding straps (black in colour and just next to the pads).
Effectiveness and biomechanics of spinal orthoses

Fig. 4. The interfacial pressures at the axillary and thoracic pads, and the tension of the axillary and thoracic straps were measured simultaneously.

subsequent visits in first 20 months of orthotic treatment (data taken at every 4-month interval). In the within-subjects analysis, the Mauchly’s test of Sphericity was applied and the Huynh-Feldt test was used for Mauchly’s W<0.05 while the Sphericity Assumed test was applied for Mauchly’s W>0.05. The confidence interval was set at 95% (p<0.05). Pearson product-moment coefficients of correlation were used to find the correlation between different parameters.

**Effectiveness of spinal orthoses**

In the analysis of the effectiveness of spinal orthoses in the treatment of moderate AIS, several parameters were considered in this study. These were spinal curvatures (Cobb’s angles in antero-posterior view and lateral view, apical vertebral rotation, trunk listing and angle of trunk inclination. The data in the first visit (pre-brace) and the 5 successive follow-up visits within the first 20 months of orthotic treatment were used for comparison.

Curve pattern distribution:
The distribution of curve pattern was 16 thoracic curves (15 right thoracic curves and 1 left thoracic curve), 8 left lumbar curves and 2 left thoracolumbar curves. Analysis was performed only on the major curves as the compensatory curves might have different responses to spinal orthoses.

Distribution of apical vertebrae:
The distribution of apical vertebrae of the 26 major curves is shown in Figure 5. The two highest frequencies of apical vertebrae occurred at the level of L2 and T8 while no apical vertebrae were found at the level of T12.
Antero-posterior Cobb’s angle:

The mean, standard deviation and range of AP Cobb’s angles at the pre-brace and the first 20 months of treatment are shown in Table 1 and Figure 6.

There was a large reduction in Cobb’s angle from standing to supine lateral bending that indicated that scoliotic spines were flexible and correctable. In comparisons among the 6 visits, the repeated measures ANOVA and the within-subjects tests (sphericity assumed) were used. There were statistically significant decreases between the pre-brace AP Cobb’s angles and the AP Cobb’s angles in the 5 successive visits. It was also found that there were significant increases in the Cobb’s angle between the 8th month and the 16th month, and the 20th month. There was a tendency for this variable to increase after the 12th month.

Table 1. Mean AP Cobb’s angles at the first 20 months of orthotic treatment.

<table>
<thead>
<tr>
<th>AP Cobb’s angle</th>
<th>Mean (±1SD)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-brace</td>
<td>34.4° (6.0°)</td>
<td>25°-45°</td>
</tr>
<tr>
<td>Pre-brace supine bending</td>
<td>6.3° (5.8°)</td>
<td>0°-15°</td>
</tr>
<tr>
<td>4th month</td>
<td>21.6° (7.6°)</td>
<td>10°-38°</td>
</tr>
<tr>
<td>8th month</td>
<td>21.1° (8.7°)</td>
<td>3°-40°</td>
</tr>
<tr>
<td>12th month</td>
<td>22.4° (8.3°)</td>
<td>9°-40°</td>
</tr>
<tr>
<td>16th month</td>
<td>23.5° (7.7°)</td>
<td>12°-39°</td>
</tr>
<tr>
<td>20th month</td>
<td>23.7° (7.7°)</td>
<td>12°-39°</td>
</tr>
</tbody>
</table>

Fig. 6. Mean AP Cobb’s angles of all the AIS patients under orthotic treatment.
The mean, standard deviation and range of lateral Cobb’s angles (thoracic kyphosis) at the pre-brace and the first 20 months of treatment are shown in Table 2 and Figure 7.

The thoracic kyphosis tended to decrease below the physiological range (20°-40°) after the 4th month. There were statistically significant decreases between the pre-brace thoracic kyphosis and the thoracic kyphosis in the 5 successive visits. In addition, there were significant reductions in thoracic kyphosis

Table 2. Mean lateral Cobb’s angles (thoracic kyphosis) at the first 20 months of orthotic treatment.

<table>
<thead>
<tr>
<th>Month</th>
<th>Mean (±1SD)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-brace</td>
<td>25.9° (9.2°)</td>
<td>14°-43°</td>
</tr>
<tr>
<td>4th month</td>
<td>21.5° (8.7°)</td>
<td>7°-45°</td>
</tr>
<tr>
<td>8th month</td>
<td>16.9° (8.2°)</td>
<td>6°-31°</td>
</tr>
<tr>
<td>12th month</td>
<td>17.9° (8.8°)</td>
<td>0°-35°</td>
</tr>
<tr>
<td>16th month</td>
<td>19.2° (9.2°)</td>
<td>0°-38°</td>
</tr>
<tr>
<td>20th month</td>
<td>18.3° (8.3°)</td>
<td>0°-34°</td>
</tr>
</tbody>
</table>

Lateral Cobb’s angle (thoracic kyphosis and lumbar lordosis):

The mean, standard deviation and range of lateral Cobb’s angles (thoracic kyphosis) at the pre-brace and the first 20 months of treatment are shown in Table 2 and Figure 7.

The mean, standard deviation and range of lateral Cobb’s angles (lumbar lordosis) at the first 20 months of orthotic application are shown in Table 3 and Figure 8.

Table 3. Mean lateral Cobb’s angles (lumbar lordosis) at the first 20 months of orthotic application.

<table>
<thead>
<tr>
<th>Month</th>
<th>Mean (±1SD)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-brace</td>
<td>41.8° (12.2°)</td>
<td>24°-68°</td>
</tr>
<tr>
<td>4th month</td>
<td>28.3° (10.8°)</td>
<td>17°-42°</td>
</tr>
<tr>
<td>8th month</td>
<td>28.1° (11.8°)</td>
<td>15°-54°</td>
</tr>
<tr>
<td>12th month</td>
<td>24.7° (7.9°)</td>
<td>17°-42°</td>
</tr>
<tr>
<td>16th month</td>
<td>27.0° (8.4°)</td>
<td>17°-45°</td>
</tr>
<tr>
<td>20th month</td>
<td>26.7° (8.4°)</td>
<td>17°-45°</td>
</tr>
</tbody>
</table>

Fig. 7. Mean thoracic kyphosis of all the AIS patients under orthotic treatment.

Fig. 8. Mean lumbar lordosis of all the AIS patients under orthotic treatment.
between the 4th month and the 8th month, and the 12th month. A significant decrease was also found between the 16th month and the 20th month.

The mean, standard deviation and range of lateral Cobb’s angles (lumbar lordosis) at the pre-brace and the first 20 months of treatment are shown in Table 3 and Figure 8. There were statistically significant decreases between the pre-brace lumbar lordosis and the lumbar lordosis in the 5 successive visits.

Apical vertebral rotation:
The mean, standard deviation and range of apical vertebral rotations at the pre-brace and the first 20 months of orthotic application are shown in Table 4. In more than 80% of cases, their apical vertebral rotation was between 5° and 20°.

There was a large reduction in apical vertebral rotation from standing to supine lateral bending that indicated that scoliotic spines were flexible and correctable. Comparisons of the pre-brace values among the 5 successive visits were made using repeated measures ANOVA. There were statistically significant reductions between the pre-brace apical vertebral rotation and the apical vertebral rotation in the 5 successive visits (except the 16th month). Additionally, significant increases were found from the 8th month to the 12th month, and to the 16th month. There was a tendency for the variable to go back to initial values after the first 12 months.

Angle of trunk inclination:
The angles of trunk inclination were measured by the Scoliometer. Spinal orthoses were taken off for these measurements. Three repeated measurements were taken for each patient at every visit and the averaged value was used. The values of angle trunk inclination at the first 20 months of orthotic treatment had small changes (mean=8.6°-8.9°, SD=3.7°-3.9°, range=2°-18°). The comparisons of the pre-brace values among the 5 successive visits were made using repeated measures ANOVA. No significant differences of the pre-brace values among the 5 successive visits were found.

Trunk listing:
Trunk listing is the trunk shifting to either left or right side of the body relative to the centre of the pelvis. Not all scoliotic patients exhibit trunk listing as some may have compensatory curves, which fully counterbalance the major curve. The values of trunk listing at the first 20 months of orthotic treatment had small changes (in-brace measurements: mean=8-10mm, SD=8-9mm, range=0-25mm; out-of-brace measurements: 10-13mm, SD=8-10mm, range=0-30mm).

For the trunk listing (in-brace), comparisons of the pre-brace values among the 5 successive visits were made using repeated measures ANOVA. There were statistically significant differences between the pre-brace trunk listing and the trunk listing (in-brace) in the 16th month and 20th month. Moreover, significant difference in the trunk listing (in-brace) between the 4th month and the 16th month was found. A significant difference between the 12th month and the 16th month was also found. For the trunk listing (out-of-brace), no significant differences of the pre-brace values among the 5 successive visits were found.

In summary, from the results of repeated measures ANOVA for the parameters shown from the previous sections, it was found that in the first 20 months of orthotic treatment, there were significant differences (decrease) in the AP Cobb’s angles, thoracic kyphosis, lumbar lordosis and apical vertebral rotation. However, generally speaking there was no significant difference between the pre-brace values and in-brace values for the angle of trunk inclination and trunk listing during the study period.

Correlation between different pairs of clinical assessment parameters:
The prediction of the in-brace values prior to orthotic application could provide an important guideline for the design, fitting and modification of spinal orthoses. In analysing the different clinical assessment parameters at the pre-brace condition and the immediate in-brace condition, there were significant reductions (p<0.05) in the antero-posterior (AP) Cobb’s angle, thoracic

<table>
<thead>
<tr>
<th>Apical vertebral rotation</th>
<th>Mean (± 1SD)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-brace</td>
<td>14.0° (6.2°)</td>
<td>5°-25°</td>
</tr>
<tr>
<td>Pre-brace supine bending</td>
<td>6.2° (7.0°)</td>
<td>0°-20°</td>
</tr>
<tr>
<td>4th month</td>
<td>11.9° (5.5°)</td>
<td>0°-25°</td>
</tr>
<tr>
<td>8th month</td>
<td>11.0° (5.5°)</td>
<td>0°-25°</td>
</tr>
<tr>
<td>12th month</td>
<td>12.1° (6.4°)</td>
<td>0°-25°</td>
</tr>
<tr>
<td>16th month</td>
<td>13.1° (6.8°)</td>
<td>0°-25°</td>
</tr>
<tr>
<td>20th month</td>
<td>11.7° (6.2°)</td>
<td>0°-25°</td>
</tr>
</tbody>
</table>
kyphosis, lumbar lordosis and apical vertebral rotation. This section aimed to determine the correlation between the pre-brace values and immediate in-brace values. The four major parameters namely AP Cobb’s angle, thoracic kyphosis, lumbar lordosis and apical vertebral rotation were considered. Pearson product-moment coefficient of correlation was performed to determine the relationship between the pre-brace values and the immediate in-brace values (Table 5).

The results of this analysis showed a high correlation between different pairs of clinical assessment parameters and their values also showed significant decrease in the study period.

Biomechanical evaluation of spinal orthoses
Mean strap tensions:
In the whole study period, the mean tension of the pelvic strap (33.9±11.3N) was found to be the highest among the four straps while the mean tension of the lumbar strap (20.7±7.4N) was the lowest in normal breathing. The tension of the axillary strap (27.8±7.8N) was higher than that of the thoracic strap (25.0±10.9N). There was a tendency for the mean strap tension to increase to a higher value in the last 12 months of the study period except for the pelvic strap.

For tension of the four straps in normal breathing, comparisons among the 5 successive visits were made using repeated measures ANOVA. No significant differences were found at the thoracic and pelvic straps. There were significant increases in tension of the axillary strap from the 4th month to the 20th month while for the lumbar strap, significant increases in tension were found from the 4th month to the 16th and 20th months.

For the measurement during deep breathing, it was found that the mean strap tension of the axillary strap and the thoracic strap were higher than those of the pelvic strap. This was because the expansion of the thoracic cage in deep breathing would increase the circumference of the chest, which would cause an increase in strap tension. The mean tension of the lumbar strap was still the lowest among the four straps. For tension of the four straps in deep breathing, comparisons among the 5 successive visits were made and no significant differences were made and no significant differences of the values among the 5 successive visits were found.

Overall mean strap tensions of spinal orthoses:
In clinical practice, it would be useful to pursue the values of individual mean strap

![Graph showing mean strap tensions](image-url)

**Fig. 9.** Overall mean strap tensions of the spinal orthoses in the treatment of AIS patients.

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Table 5. The correlation of the four major parameters with each other in the study period (level of significance, *p<0.05*).

<table>
<thead>
<tr>
<th>Correlation coefficients</th>
<th>AP Cobb’s angle</th>
<th>Thoracic kyphosis</th>
<th>Lumbar lordosis</th>
<th>Apical vertebral rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP Cobb’s angle</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Thoracic kyphosis</td>
<td>0.852 (*p=0.031)</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Lumbar lordosis</td>
<td>0.928 (*p=0.008)</td>
<td>0.898 (p=0.015)</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Apical vertebral rotation</td>
<td>0.827 (*p=0.042)</td>
<td>0.803 (p=0.055)</td>
<td>0.716 (p=0.109)</td>
<td>—</td>
</tr>
</tbody>
</table>
tension as well as the overall mean strap tension. The overall mean strap tensions of the spinal orthoses in the treatment of AIS patients are shown in Figure 9. In the study period, it was found that the mean difference and standard deviation in the strap tensions between the deep breathing activity and the normal breathing activity was 10.3N and 0.8N respectively.

For the overall strap tension at normal breathing, comparisons among the 5 successive visits were made using repeated measures ANOVA. There were statistically significant increases in the strap tensions from the 4th month to the 16th and 20th months, and also from the 12th to the 16th and 20th months. For the overall strap tension at deep breathing, comparisons among the 5 successive visits were made and no significant differences of the values among the 5 successive visits were found.

Interfacial pressures between the patient’s body and the spinal orthosis:

In the normal breathing activity, the mean pressure of the thoracic pad was 9.34±3.39kPa (70.5±25.4mmHg) and was the highest among the four pads while the mean pressure of the pelvic pad was the lowest at 4.95±18.90kPa (37.1±14.1mmHg) (Fig. 10).

For pressure of the four pads at normal breathing, comparisons among the 5 successive visits were made using repeated measures ANOVA. No significant differences were found at the thoracic, lumbar and pelvic pads but there were significant increases in pressure of the axillary pad from the 4th month to the 12th and 20th months. In the study period, a tendency for pressure of the axillary pad to increase was noted. However, the mean pressure of the lumbar pad and pelvic pad varied within a small range.

In deep breathing, the mean pressure of the thoracic pad was found to be the highest among the four pads while the mean pressure of the pelvic pad was still the lowest. For pressure of the four pads at deep breathing, comparisons among the 5 successive visits were made and no significant differences were found at the lumbar and pelvic pads but there were significant decreases in pressure for both the axillary and thoracic pads from the 4th month to the 16th and 20th months. It was noted that there was a tendency for the mean pressure of the axillary pad and the thoracic pad to decrease in the study period, possibly due to a decrease in chest expansion. However, the mean pressure of lumbar pad and pelvic pad varied within a small range.

Mean pad pressures of the four pressure pads:

In was found that the mean pad pressure of the thoracolumbar curve pattern had the lowest value 5.59±1.35kPa (41.9±10.1mmHg) in normal breathing activity while the mean pad pressure of the thoracic curve pattern had the highest value (7.84±3.12kPa (58.8±23.4mmHg) in deep breathing activity. The mean difference of pad pressure between normal and deep breathing in the lumbar, thoracolumbar and thoracic curve patterns were 0.31, 0.75 and 0.67kPa (2.3, 5.6 and 5mmHg) respectively.

Overall mean pressures of the four pads:

Similarly to studying the overall mean strap tension, it would be useful to have a better understanding about the average value of pressure acting on the body. In the study period,
it was found that the mean difference in the pad pressures between normal breathing activity and deep breathing activity in the first 20 months of treatment decreased from 1.63 to 0.24kPa (12.2 to 1.8mmHg). This might be due to the increasing physical constraint from the rigid orthoses in deep breathing.

For the pad pressure at the normal breathing, comparisons among the 5 successive visits were made using repeated measures ANOVA. No significant differences of the values among the 5 successive visits were found. The same result was noted in the deep breathing activity.

For normal breathing, the mean pressure of the four pads was found to be 7.09±1.77kPa (53.2±13.3mmHg) while the mean tension of the four straps was 26.8±5.2N. The pressure at the four pads and the tension of the four straps were strongly correlated and the correlation coefficient was 0.873 (p<0.05). An increase in the strap tension would have a tendency to raise the pad pressure and vice versa. Cobb’s angle significantly correlated with the pad pressure and strap tension. It could be presumed that the strap tension was increased thus the pad would give a higher pressure aiming at better control of the deteriorating curves during the treatment period. Apical vertebral rotation, thoracic kyphosis and lumbar lordosis had no significant correlation with either the pad pressure or the strap tension. It could be presumed that a change in pad pressure would not have a tendency to alter these three parameters.

In deep breathing activity, the mean pressure of the four pads was found to be 7.83±2.15kPa (58.7±16.1mmHg) while the mean tension of the four straps was 37.1±6.9N. There was no significant correlation between the pad pressure and the strap tension (correlation coefficient=-0.136, p=0.828). The pad pressure and the strap tension also showed no significant correlation with Cobb’s angle, thoracic kyphosis, lumbar lordosis, and apical vertebral rotation. It could be noted that those parameters measured from the radiographs were taken while the breath was held, but this was not necessarily a deep breath. Therefore, the results of the analysis could not really reflect the trend of change of those parameters during deep breathing activities.

Discussion

Effectiveness of spinal orthoses

The results of the current study suggest that in moderate AIS (AP Cobb’s angle between 25° and 45°), orthotic treatment could significantly reduce the AP Cobb’s angle (p<0.000), thoracic kyphosis (p<0.007), lumbar lordosis (p<0.005) as well as apical vertebral rotation (p<0.03 except at the 16th month p=0.327) in the first 20 months of treatment. There was a tendency for the studied parameters to be reduced to their lowest values in the first 12 months of treatment and then they increased again. However, values for months 16 and 20 were still below the pre-brace values. The current findings of AP Cobb’s angle, apical vertebral rotation and trunk listing that partially agreed with Willers et al. (1993) showed that there were immediate decreases in the values but the best improvements could not be maintained in subsequent follow-ups.

The lowest value of Cobb’s angle or best control of lateral curvature within the first 12 months of orthotic treatment was also reported by Noonan et al. (1996), Lonstein and Winter (1988), Cochran and Nachemson (1985), Carr et al. (1980) Edmonson and Morris (1977), Keiser and Shufflebarger (1976). The reason for this phenomenon was suggested to be that once the orthotic treatment started there were persistent external forces applied to the torso, together with in-brace and out-of-brace physical exercises regularly performed by the patient, thus the tightened soft tissues including muscular and ligamentous structures would be relaxed. This would help to improve the trunk alignment and spinal curvature. However, with the growing scoliotic spine, the involved vertebrae might not grow vertically but laterally. This is because in an offset scoliotic spine, the vertebrae would grow under uneven stress and thus their bodies would form in a wedge shape (Von-Volkman, 1862). This might cause the curvature to increase again. Therefore, the first 12 months of orthotic treatment would be critical in controlling the scoliotic deformity.

This series also showed decreases in thoracic kyphosis and lumbar lordosis. In controlling the coronal curvatures, precautions as suggested by Dansereau et al. (1996) need to be taken for the prevention of exaggerated reduction of the sagittal curvatures, leading to lumbar lordosis as well as thoracic kyphosis beyond their physiological range (20°-40° for thoracic kyphosis and 30°-50° for lumbar lordosis). This might cause pulmonary problem, spinal instability and patient discomfort (Dansereau et al., 1996).
From the current results, orthotic treatment seemed to render no significant change to the trunk listing (including in-brace and out-of-brace) and angle of trunk inclination in the first 20 months of treatment. Rudicel and Renshaw (1983) carried out a related study on the effect of spinal orthoses on trunk listing in idiopathic scoliosis with an average treatment period of 47 months and found that there was no predictable improvement in trunk listing despite consistent orthotic treatment. He pointed out that changes in trunk listing did not correlate with length of time wearing an orthosis, initial changes in curve magnitude, or skeletal age at which treatment was begun. However, in a growing scoliotic spine, the lateral offset (trunk listing) of the curve might or might not be counterbalanced by its compensatory curve. For uncounterbalanced progressive curves, their trunk listing might be increasing. A stable trunk listing maintained by the spinal orthosis has demonstrated a control to the progressive scoliotic spine.

The correlations of different pairs of the four clinical assessment parameters, namely AP Cobb’s angle, thoracic kyphosis, lumbar lordosis and apical vertebral rotation were investigated and high correlations were found. It could be explained using the coupling effect and righting reflex in the spinal column (White and Panjabi 1990). Coupling means that the lateral flexion and vertebral rotation occur simultaneously and the righting reflex is used to describe the concurrent change between the thoracic kyphosis and lumbar lordosis. Therefore, the AP Cobb’s angle (lateral flexion angle) varied with the vertebral rotation while the thoracic kyphosis changed with the lumbar lordosis. To a certain extent, there was some overlapping between these two phenomena. Lindh (1980) reported that a reduction in lumbar lordosis would decrease the AP Cobb’s angle.

**Biomechanical evaluation of spinal orthoses**

One of the main objectives in this study was to discover the change of correcting pressure/force prescribed by the treating orthotist during the study period. As was discussed in the previous section the major clinical assessment parameters such as Cobb’s angle showed best control (reduced from 34.4° to 21.1°) at the 8th month of orthotic application and then increased again (to 23.7°) after 20 months of orthotic treatment. However, the angle was still below the pre-brace value. The changes of those biomechanical parameters such as pad pressure and strap tension were studied in both normal breathing and deep breathing activities. Their correlations with the major clinical assessment parameters were also investigated.

The current results were consistent with the findings of Wong (1995), Chase et al. (1989) and Winter and Carlson (1977) that modification of strap tension would influence the forces exerted by the compression pads of the orthosis and Jiang et al. (1992) even demonstrated alterations in the progression of scoliotic curves. Therefore, to prevent the biomechanical action of the orthosis on the torso becoming less efficient, the straps of the orthosis should be regularly adjusted by the treating orthotist.

Moreover, it was found that the correlation between the mean AP standing Cobb’s angle and the mean pad pressure, and the mean strap tension were highly significant and their corresponding correlation coefficients were 0.931 (p<0.05) and 0.914 (p<0.05). It was noted that the AP Cobb’s angle was increasing with the strap tension and pad pressure after the 8th month of treatment. This change might be due to further collapse of the scoliotic curve which would exert larger lateral leaning forces on the orthosis, thus increasing the pad pressures and strap tensions or the treating orthotist might deliberately increase the strap tension in an attempt to prevent further curve deterioration. On the other hand, neither the pad pressure nor strap tension showed significant correlation (all the p values >0.05) with the apical vertebral rotation, thoracic kyphosis or lumbar lordosis. Therefore, it could be presumed that a change in pad pressure or strap tension would not have a tendency to alter the value of these three clinical assessment parameters.

During deep breathing, the mean pressure of the four pads was found to be 7.93±2.15kPa (58.7±16.1mmHg) while the mean tension of the four straps was 37.1±6.9N. Branemark (1976) pointed out that pressure sores and ulceration would occur if pressure was applied on the skin over a long period and over the range of 5.33 to 8.00kPa (40 to 60mmHg). Clinically, patients seldom complained of pressure sensitivity, and there was no tissue breakdown caused by the pressure pads. This was probably due to the fact that although the magnitude of pressure was marginal, it could be relieved intermittently by...
motion of the patient's trunk. In deep breathing, the pad pressure was not strongly correlated with the strap tension (r=0.136, p=0.828). Similarly, the pad pressure had no significant correlation with that of the Cobb's angle, thoracic kyphosis, lumbar lordosis and apical vertebral rotation during deep breathing. It could be noted that those parameters measured from the radiographs were taken from the condition that breath was held but this was not necessarily a deep breath. Therefore, the results of the analysis could not really reflect the changes of those parameters during deep breathing.

Although there were no significant changes in pad pressure in normal and deep breathing activities, the mean difference in pad pressure between the two breathing activities was decreasing from 1.63 to 0.24kPa (12.2 to 1.8mmHg) in the first 20 months of orthotic treatment. As the chest size would change in breathing the interfacial pressure between the chest and the pressure pads would change accordingly. The prolonged application of the rigid orthoses might render some physical constraint in chest expansion that would affect the breathing pattern or pulmonary function of the patients. In a long-term study of the effectiveness of the Boston brace treatment for idiopathic scoliosis, Willers et al. (1993) noted a reduction in the sagittal diameter of the chest and pointed out its importance for pulmonary function and cosmesis. Korovessis et al. (1996) and Refsum et al. (1990) studied long-term alterations of respiratory function in AIS patients under orthotic treatment and found that, for moderate curves, there was no persistent deterioration of pulmonary function as compared with the pre-brace stage.

Currently, there is no standardised strap tension and pad pressure under which the spinal orthosis should be applied to achieve optimal control and good outcomes. This study demonstrated that the pad pressure and strap tension were strongly correlated. The function of the spinal orthosis might mainly focus upon how tightly the orthosis is fastened. For enhancing the effectiveness of orthotic treatment, an independent standard tension should be set in each strap, and regular and close monitoring is also needed.

**Conclusion**

In the first 20 months of orthotic treatment for moderate AIS patients, the values of standing AP Cobb's angle, apical vertebral rotation, lumbar lordosis as well as thoracic kyphosis showed reduction, however, the angle of trunk inclination and trunk listing did not. The values of those reducible parameters reached their lowest values within the first 12 months of orthotic treatment and then the values gradually increased but they were still significantly below the pre-brace values.

This study demonstrated that the pad pressure and strap tension were strongly correlated, thus in assessing the function of spinal orthosis, examiners can focus upon how tightly the orthosis is fastened. For enhancing the effectiveness of orthotic treatment, an independent standard tension should be set in each strap, and regular and close monitoring is also needed.

**REFERENCES**


