■ SPINE

Supine correction index as a predictor for brace outcome in adolescent idiopathic scoliosis

L. P. K. Wong,
P. W. H. Cheung,
J. P. Y. Cheung

From The University of Hong Kong, Hong Kong, China

Aims

The aim of this study was to assess the ability of morphological spinal parameters to predict the outcome of bracing in patients with adolescent idiopathic scoliosis (AIS) and to establish a novel supine correction index (SCI) for guiding bracing treatment.

Methods

Patients with AIS to be treated by bracing were prospectively recruited between December 2016 and 2018, and were followed until brace removal. In all, 207 patients with a mean age at recruitment of 12.8 years (SD 1.2) were enrolled. Cobb angles, supine flexibility, and the rate of in-brace correction were measured and used to predict curve progression at the end of follow-up. The SCI was defined as the ratio between correction rate and flexibility. Receiver operating characteristic (ROC) curve analysis was carried out to assess the optimal thresholds for flexibility, correction rate, and SCI in predicting a higher risk of progression, defined by a change in Cobb angle of ≥ 5° or the need for surgery.

Results

The baseline Cobb angles were similar ($p = 0.374$) in patients whose curves progressed (32.7° (SD 10.7)) and in those whose curves remained stable (31.4° (SD 6.1)). High supine flexibility (odds ratio (OR) 0.947 (95% CI 0.910 to 0.984); $p = 0.006$) and correction rate (OR 0.926 (95% CI 0.890 to 0.964); $p < 0.001$) predicted a lower incidence of progression after adjusting for Cobb angle, Risser sign, curve type, menarche status, distal radius and ulna grading, and brace compliance. ROC curve analysis identified a cut-off of 18.1% for flexibility (sensitivity 0.682, specificity 0.704) and a cut-off of 28.8% for correction rate (sensitivity 0.773, specificity 0.691) in predicting a lower risk of curve progression. A SCI of greater than 1.21 predicted a lower risk of progression (OR 0.4 (95% CI 0.251 to 0.955); sensitivity 0.583, specificity 0.591; $p = 0.036$).

Conclusion

A higher supine flexibility (18.1%) and correction rate (28.8%), and a SCI of greater than 1.21 predicted a lower risk of progression. These novel parameters can be used as a guide to optimize the outcome of bracing.

Cite this article: *Bone Joint J* 2022;104-B(4):495–503.

Introduction

Bracing is the standard nonoperative treatment for adolescent idiopathic scoliosis (AIS) with curve magnitude of ≥ 20° (± 5°).[1] Bracing is an effective method of reducing the risk of radiological curve progression and reaching the threshold for surgery.[2] Although it has been shown that bracing has a success rate of 72% in preventing curve progression to the surgical threshold,[2] the outcome of bracing varies despite similar rates of patient compliance with treatment.[3] It is important that clinicians are able to predict the outcome of bracing in order to address the treatment expectations of patients and their families.

The factors commonly used to predict brace outcome are related to age and skeletal maturity,[4-7] as immaturity implies potential for growth and, therefore, curve progression. However, as bracing

Correspondence should be sent to J. P. Y. Cheung; email: cheungjp@hku.hk

doi:10.1302/0301-620X.104B4.BJJ-2021-1220.R1 $2.00

Bone Joint J
2022;104-B(4):495–503.

Table I. Baseline characteristics of patients.

Parameters	Cohort	Stable patients	Progressed patients	p-value*
Total, n	207	162	45	
Sex, n (%)				0.127
Male	35 (16.9)	24 (14.8)	11 (24.4)	
Female	172 (83.1)	138 (85.2)	34 (75.6)	
Mean age, years (SD)	12.8 (1.2)	12.9 (1.1)	12.6 (1.3)	0.118
Mean prebrace Cobb angle, ° (SD)	31.7 (7.3)	31.4 (6.1)	32.7 (10.7)	0.414
Mean outcome Cobb angle, ° (SD)	31.4 (11.1)	27.7 (7.2)	45.0 (12.1)	< 0.001
Post-menarche, n (% of females)	95 (57.6)	83 (62.4)	12 (37.5)	0.010
Mean standing height, cm (SD)	155.9 (7.1)	156.2 (7.0)	154.9 (7.4)	0.293
Mean sitting height, cm (SD)	83.0 (4.8)	83.4 (4.5)	81.3 (5.3)	0.009
Mean arm span, cm (SD)	155.7 (27.4)	156.6 (28.6)	152.5 (22.7)	0.381
Mean weight, kg (SD)	43.0 (6.7)	43.3 (6.1)	41.7 (8.5)	0.151
Mean BMI, kg/m^2 (SD)	17.6 (2.1)	17.7 (2.0)	17.3 (2.6)	0.262
Risser stage, n (%)				0.045
0	65 (34.9)	43 (29.7)	22 (53.7)	
1	36 (19.4)	27 (18.6)	9 (22.0)	
2	49 (26.3)	43 (29.7)	6 (14.6)	
3	29 (15.6)	25 (17.2)	4 (9.8)	
4	6 (3.2)	6 (4.1)	0 (0.0)	
5	1 (0.5)	1 (0.7)	0 (0.0)	
Radius grade, n (%)				0.070
5	5 (3.3)	2 (1.8)	3 (8.1)	
6	26 (17.3)	16 (14.2)	10 (27.0)	
7	41 (27.3)	31 (27.4)	10 (27.0)	
8	74 (49.3)	60 (53.1)	14 (37.8)	
9	4 (2.7)	4 (3.5)	0 (0.0)	
Ulna grade, n (%)				0.059
3	1 (0.5)	0 (0.0)	1 (2.7)	
4	5 (2.4)	3 (2.7)	2 (5.4)	
5	34 (16.4)	21 (18.6)	13 (35.7)	
6	69 (33.3)	53 (46.9)	16 (43.2)	
7	40 (19.3)	35 (31.0)	5 (13.5)	
8	1 (0.5)	1 (0.9)	0 (0.0)	
Mean thoracic rib hump, ° (SD)	7.3 (3.1)	7.2 (3.2)	7.8 (3.1)	0.296
Mean lumbar rib hump, ° (SD)	6.8 (3.1)	6.8 (3.0)	6.9 (3.7)	0.930
Mean compliance, hr (SD)	13.2 (6.2)	14.1 (6.0)	9.8 (5.6)	< 0.001
Mean T5–T12 kyphosis, ° (SD)	17.8 (10.7)	17.9 (10.8)	17.6 (10.1)	0.885
Mean L1–S1 lordosis, ° (SD)	52.9 (13.1)	52.7 (13.2)	53.5 (13.0)	0.705
Mean SS, ° (SD)	41.0 (10.6)	40.4 (10.3)	43.2 (11.6)	0.129
Mean PI, ° (SD)	47.3 (13.4)	46.7 (13.5)	49.6 (12.8)	0.206
Mean PT, ° (SD)	7.8 (8.6)	8.0 (8.9)	6.9 (7.4)	0.458
Mean sagittal vertical axis, cm (SD)	19.2 (14.8)	19.9 (15.0)	16.5 (13.8)	0.167
Mean shoulder height, cm (SD)	7.3 (5.8)	7.2 (5.4)	7.8 (7.1)	0.567
Mean truncal shift, cm (SD)	11.8 (8.9)	11.9 (9.1)	11.4 (8.6)	0.738
Mean C7–CSVL, cm (SD)	13.8 (9.8)	13.8 (9.8)	13.7 (9.8)	0.934
Mean T1 tilt, ° (SD)	3.9 (3.6)	3.8 (3.5)	4.2 (3.7)	0.513
Curve type, n (%)				0.040
Thoracic	110 (53.1)	80 (49.4)	30 (66.7)	
Lumbar	97 (46.9)	82 (50.4)	15 (33.3)	
Mean apical vertebra wedging, ° (SD)	5.0 (2.5)	4.8 (2.4)	5.7 (2.8)	0.038
Mean change in apical vertebra wedging, ° (SD)	0.6 (3.6)	0.2 (3.2)	2.1 (4.8)	0.012
Mean upper disc angulation, ° (SD)	5.0 (3.0)	5.0 (3.0)	5.0 (3.0)	0.874
Mean lower disc angulation, ° (SD)	4.9 (3.0)	4.8 (2.8)	5.0 (3.5)	0.660
Mean apical ratio (SD)	1.2 (0.7)	1.2 (0.7)	1.2 (0.1)	0.793
Mean flexibility, % (SD)	23.2 (15.6)	25.5 (14.5)	14.9 (17.1)	< 0.001
Mean correction rate, % (SD)	33.7 (19.5)	37.3 (18.1)	20.9 (18.9)	< 0.001

*Independent-samples *t*-test.
CSVL, central sacral vertical line; PI, pelvic incidence; PT, pelvic tilt; SD, standard deviation; SS, sacral slope.

Table II. Univariable logistic regression for prediction of curve progression.

Parameters	Odds ratio (95% CI)	p-value
Baseline Cobb angle	1.024 (0.981 to 1.068)	0.273
T5-T12 kyphosis	0.998 (0.967 to 1.029)	0.884
L1-S1 lordosis	1.005 (0.980 to 1.030)	0.704
SS	1.024 (0.993 to 1.056)	0.130
PI	1.016 (0.991 to 1.040)	0.207
PT	0.985 (0.948 to 1.024)	0.456
SVA	0.983 (0.959 to 1.007)	0.168
Shoulder height difference	1.019 (0.964 to 1.077)	0.502
Truncal shift	0.994 (0.957 to 1.032)	0.737
C7-CSVL	0.999 (0.944 to 1.123)	0.933
T1 tilt	1.029 (0.947 to 1.126)	0.513
Curve type	2.050 (1.026 to 4.096)	0.042
Apical vertebra wedging	1.146 (1.006 to 1.306)	0.040
Upper disc angulation	1.009 (0.904 to 1.126)	0.873
Lower disc angulation	1.025 (0.918 to 1.146)	0.659
Apical ratio	0.918 (0.478 to 1.761)	0.796
Flexibility	0.956 (0.934 to 0.978)	< 0.001
Correction rate	0.951 (0.931 to 0.971)	< 0.001
Age	0.797 (0.599 to 1.061)	0.120
Menarche status	0.361 (0.163 to 0.802)	0.012
Standing height	0.974 (0.928 to 1.023)	0.292
Sitting height	0.917 (0.854 to 0.984)	0.016
Arm span	0.993 (0.978 to 1.008)	0.367
Weight	0.961 (0.911 to 1.014)	0.151
BMI	0.909 (0.772 to 1.074)	0.262
Risser stage	0.588 (0.421 to 0.822)	0.002
Radius grade	0.566 (0.376 to 0.852)	0.006
Ulna grade	0.496 (0.312 to 0.789)	0.003
Thoracic rib hump	1.064 (0.947 to 1.195)	0.295
Lumbar rib hump	1.006 (0.889 to 1.138)	0.930
Mean compliance	0.888 (0.837 to 0.943)	< 0.001

CI, confidence interval; CSVL, central sacral vertical line; PI, pelvic incidence; PT, pelvic tilt; SS, sacral slope; SVA, sagittal vertical axis.

alters the natural history of AIS, metrics for measuring the effect of bracing, such as in-brace correction of Cobb angle, may play an important role in predicting the outcome of bracing. In-brace Cobb angle correction has been shown to predict brace outcome by several longitudinal studies.[8-10] Correction rate is also closely related to supine flexibility,[11,12] which, in turn, is prognostic of brace outcome.[13] As a reliable and modifiable factor, correction rate can serve as a guiding metric for clinicians and orthotists to refine the brace design and improve brace outcomes, such as increasing pressure padding at the apex to more closely resemble the inherent curve flexibility.[14,15] However, there is no information available to help clinicians and orthotists achieve optimal brace correction on the basis of the intrinsic flexibility of the individual patient.

Non-modifiable intrinsic variations in spinal and trunk morphology may also play a role in brace function. Factors previously examined in the literature include the spinopelvic relation,[16,17] vertebral rotation,[11,18] curve type,[19] and curve flexibility.[11,13] However, there is a lack of prospective studies with sufficient sample size to examine the effect of these morphological factors on the outcome of bracing.

Therefore, the purpose of this study was to identify the predictive ability of correction rate and flexibility, to introduce a novel index for correction rate with respect to supine flexibility, and to examine the predictive ability of curve morphology in braced patients with AIS.

Methods

A prospective cohort of 392 consecutive patients with AIS, who were to undergo custom-moulded Boston or Milwaukee bracing in our hospital, were recruited between December 2016 and December 2018. Patients were braced according to the Scoliosis Research Society (SRS) criteria (less than one year post-menarche; major curve magnitude between 25° and 40°; Risser stage ≤ 2; no previous treatment),[20] with two additional considerations. First, patients with Risser stage> 2 were braced if they had a radius grade ≤ 8 or ulna grade ≤ 7,[21,22] according to the distal radius and ulna classification (DRU).[23] This was because Risser staging offers limited information about the timing of the adolescent growth spurt compared to the DRU,[21,24,25] and patients with a radius grade of 8 and ulna grade of 7 still have significant potential for growth and curve progression.[21,22] Second, patients with curve ≥ 35° were braced if they had a radius grade ≤ 9 or ulna grade ≤ 8, regardless of Risser staging, as it has been shown that these patients have high and moderate risks of progression to 40° and 50°, respectively.[26] Patients were followed to brace removal. Patients were weaned when they were ≥ two years post-menarche, with Risser stage ≥ 4, and had no further increase in body height and arm span over six months.[27,28] Of the 392 patients enrolled, 172 were excluded due to ongoing brace treatment and 13 due to missing supine radiographs, leaving 207 patients for analysis. Of these, 172 patients (83.1%) were female. Mean age of this cohort was 12.8 years (standard deviation (SD) 1.2) and majority of the cohort (150 patients) had a Risser stage of 0 to 2 (Table I). Ethical approval for this study was provided by the local hospital review board.

Brace fabrication and fitting. Braces were made by negative casting from a supine radiograph obtained on the day of brace initiation. Three orthotists (LC, VY, NPF) were involved with the fabrication process of all patients in the study. During fabrication, the patient is scanned with a handheld optical scanner and casting is made by plastic sheet wrapping. The brace design is a computer-aided process done by applying derotation forces above and below the apex. Fitting is done by additional trimlining. Patients are advised to wear a proper undershirt, maintain an upright posture, and accept the brace being applied with as much tightness as they can tolerate. Another standing in-brace radiograph was taken two weeks after wearing the newly fitted brace to assess correction.

The brace was prescribed to be worn for 20 hours a day and brace compliance was monitored with the aid of Thermochron iButtons thermal sensors (Maxim Integrated Products, USA).[29] Compliance was measured as mean hours of wearing per day. The brace would be recorded as being worn if the thermal sensor detected temperature from 29.4°C to 36.7°C. Regular follow-ups were given every four to six months, depending on the severity of the curve and risk of progression. Patients followed a nocturnal weaning protocol over a period of six months before complete removal. The outcome radiograph was

Table III. Multivariable logistic regression of parameters with p-value > 0.25 in univariable analysis, each adjusted for baseline Cobb angle, Risser sign, curve type, menarche status, distal radius and ulna classification, and average brace compliance.

Parameters	OR (95% CI)	p-value	Change in -2 log likelihood	p-value
SS	1.081 (1.018 to 1.149)	0.012	9.548	0.002
PI	1.057 (1.013 to 1.104)	0.011	7.731	0.005
SVA	0.988 (0.946 to 1.032)	0.600	1.042	0.307
Apical vertebra wedging	0.974 (0.794 to 1.194)	0.797	0.056	0.456
Flexibility	0.947 (0.910 to 0.984)	0.006	12.349	< 0.001
Correction rate	0.926 (0.890 to 0.964)	< 0.001	24.423	< 0.001

CI, confidence interval; OR, odds ratio; PI, pelvic incidence; SS, sacral slope; SVA, sagittal vertical axis.

chosen as the out-of-brace radiograph taken on the day of brace weaning, or the last out-of-brace radiograph before initiation of surgery. Patients were advised to remove the brace 24 hours prior to taking out-of-brace radiographs to allow for rebound from brace correction.

Study parameters. Demographic data included sex, age, menarche status, arm span, weight, standing height, BMI, sitting height, and clinical rib hump measured by scoliometer (PWHC). Baseline radiological data were obtained from pre-brace standing posteroanterior and lateral whole-spine radiographs, a supine posteroanterior radiograph, and immediate in-brace posteroanterior and lateral standing radiographs. Radiological parameters (measured by and LPKW and JPYC on the Picture archiving and Communication System; GE Healthcare, USA) included the major curve Cobb angle, shoulder height difference, truncal shift, truncal listing (C7-central sacral vertical line offset), T1 tilt, major curve apex location, apical vertebral wedging, apical ratio, and disc angulation of the upper and lower intervertebral discs adjacent to the apex. Sagittal parameters included T5–T12 kyphosis, L1–S1 lordosis, sacral slope (SS), pelvic incidence (PI), pelvic tilt (PT), and the sagittal vertical axis (SVA). The detailed definitions of these predictors are listed in Supplementary Table i. The status of the iliac crest apophysis on the pre-brace radiographs was used to determine the Risser stage and an additional left-hand radiograph was obtained at baseline to determine the DRU for skeletal age.[30] Major curve flexibility and correction rate were determined from the supine and first in-brace radiographs respectively,[12,13] by the formulae:

$$Flexibility = \frac{prebrace\ Cobb\ angle - supine\ Cobb\ angle}{prebrace\ Cobb\ angle} \times 100\%$$

$$Correction\ rate = \frac{prebrace\ Cobb\ angle - first\ inbrace\ Cobb\ angle}{prebrace\ Cobb\ angle} \times 100\%$$

An additional parameter, called the supine correction index (SCI) was defined as follows:

$$Supine\ correction\ index = \frac{Correction\ rate}{Flexibility} \times 100\%$$

Mean brace compliance, obtained from the thermal sensor embedded in the brace, was recorded as the mean number of hours of brace wear per day over the entire period of bracing.

Statistical analysis. Data analysis was done with SPSS v. 26.0 (IBM, USA) and R v. 4.0.4 (R Foundation for Statistical Programming, Austria). Curve progression in this study was defined as an increase in major curve Cobb angle > 5° on the outcome radiograph compared to baseline, or the incidence of surgery. Otherwise, a patient was deemed to have no curve progression. Predictors studied are radiological parameters detailed in Supplementary Table i, plus flexibility, correction rate, and SCI. For prediction of progression status, univariable analysis was performed with univariable logistic regression for each predictor variable. Variables with p-value < 0.25 were selected to enter multivariable logistic regression,[31] which was adjusted for a set of established radiological and maturity predictors in the literature, determined a priori, including initial Cobb angle, Risser stage, curve type, menarche status, DRU, and brace compliance. Multicollinearity problems in the model were assessed by the variance inflation factor (VIF) and they were found to be satisfactory. The p-values and adjusted odds ratios (ORs) of these predictors along with their respective 95% confidence intervals (CIs) were identified. Ideal cut-off values for flexibility, correction rate, and SCI were determined by the receiver operating characteristic (ROC) curve analysis, and the area under curve (AUC), specificity, and sensitivity were investigated. Optimal cut-offs were determined by selecting the point closest to 0.1 on the curve.[32] A linear correlation plot between the pre-brace Cobb angle and supine Cobb angle was plotted, and the coefficient of determination (R^2) was calculated. Statistical significance was defined by a significance level of 5% for all tests.

Table IV. Receiver operating characteristic curve analysis for optimal cut-offs.

Parameters	Optimal cut-off	AUC	Sensitivity	Specificity
Flexibility, %	18.1	0.686	0.682	0.704
Correction rate, %	28.8	0.736	0.773	0.691
SCI	1.21	0.583	0.591	0.605

AUC, area under the curve; SCI, supine correction index.

Results

The mean Cobb angles were 31.7° (SD 7.3°) and 31.4° (SD 11.1°) before and after treatment respectively. The mean flexibility and correction rate were 23.2% (SD 15.6%) and 33.7% (SD 19.5%), respectively.

Of the 207 patients, 162 had stable curves while 45 experienced curve progression. Only 16 out of 207 patients (7.7%) progressed to the surgical threshold of 50° or underwent surgery. The outcome Cobb angle was significantly different between the stable and progressed groups (p < 0.001, independent-samples *t*-test). Among the 150 patients satisfying the standard SRS criteria for bracing, 37 showed progression (24.6%). For the 57 patients not satisfying the standard SRS criteria but were included based on their DRU status and Cobb angle, only eight progressed (14%). The difference in proportion of patients who progressed did not reach statistical significance (p = 0.098, independent-samples *t*-test). There was no significant difference

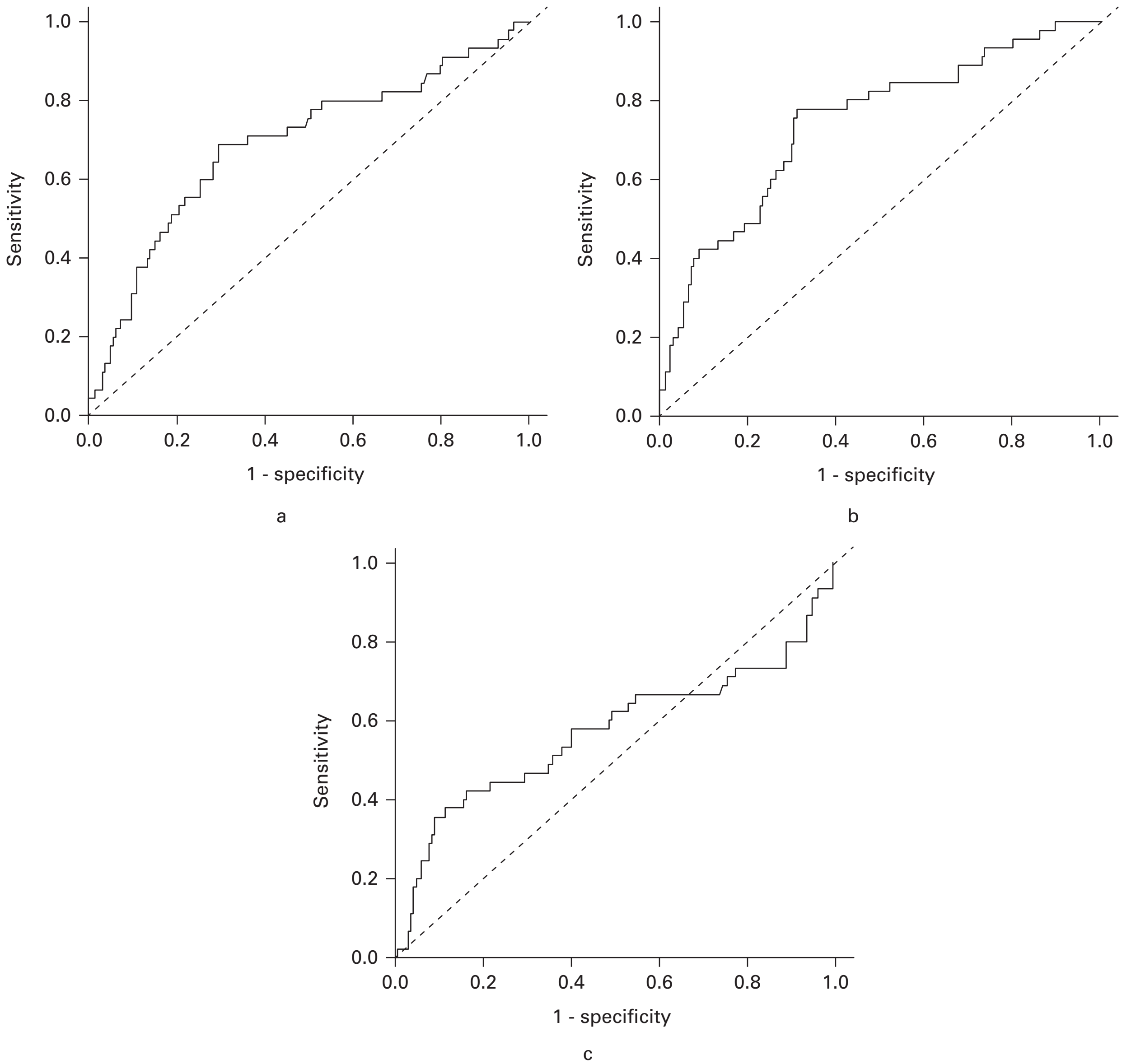

Fig. 1

Receiver operating characteristic curve for a) flexibility, b) correction rate, and c) supine correction index in predicting progression outcome.

between the stable and progressing groups in baseline Cobb angle (p = 0.414, independent-samples *t*-test), standing height (p = 0.293, independent-samples *t*-test), weight (p = 0.151, independent-samples *t*-test), and BMI (p = 0.262, independent-samples *t*-test). When univariable logistic regressions were fitted for each of the radiological and maturity predictors, apical vertebra wedging, flexibility, correction rate, menarche status, sitting height, Risser stage, radius grade, ulna grade, and mean brace compliance were found to be significantly predictive of curve for curve progression (Table II).

Among factors selected to enter multivariable logistic regression, SS, PI, flexibility, and correction rate were significantly predictive of progression, adjusted for baseline Cobb angle, Risser stage, curve type, menarche status, DRU, and mean brace compliance (Table III).The multivariable prediction model was significantly improved by the addition of both flexibility (p < 0.001; likelihood ratio test) and correction rate (p < 0.001; likelihood ratio test).

The ROC curves for supine flexibility, correction rate, and SCI are presented in Figure 1 and the performance metrics are detailed in Table IV. The AUC for flexibility was 0.686 and the optimal cut-off was 18.1%, with a sensitivity of 0.682 and a specificity of 0.704. Flexibility above 18.1% was significantly predictive of lower risk of progression (OR 0.188 (95% CI 0.092 to 0.383); p < 0.001, chi-squared test). The AUC for correction rate was 0.736, and the optimal cut-off was 28.8% with a sensitivity of 0.773 and a specificity of 0.691. Patients with correction rate above 28.8% had an OR of 0.129 (95% CI 0.059 to 0.281; p < 0.001, chi-squared test) for curve progression. The SCI had an AUC of 0.583 and an optimal cut-off of

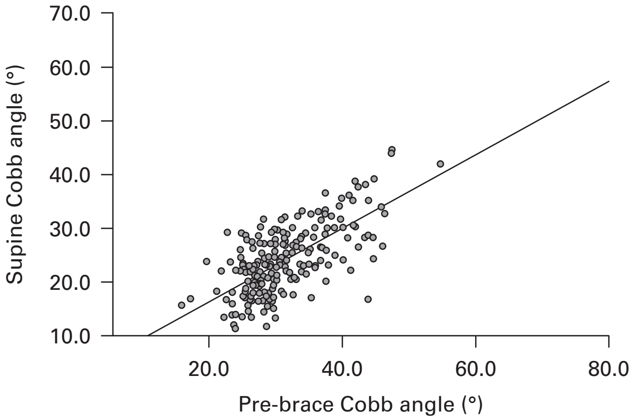

Fig. 2

Correlation between supine and pre-brace Cobb angle. R^2 linear = 0.527.

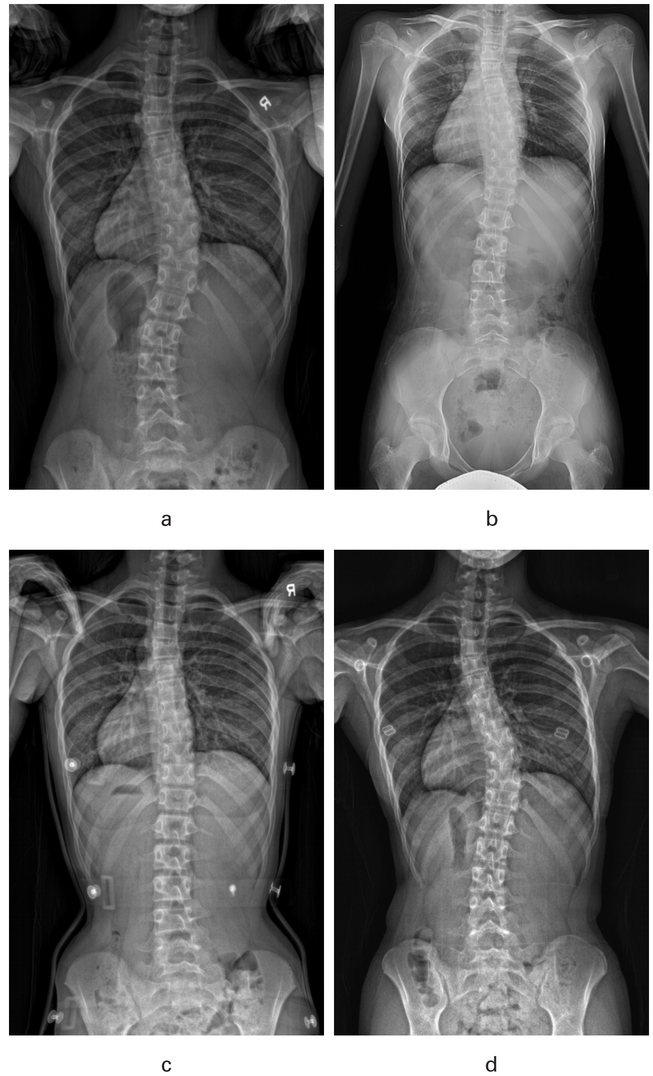

Fig. 3

a) Pre-brace radiograph for a 12-year-old female with T7-L1 Cobb angle of 33.2° at Risser 0, with apex at T10 and radius grade of 8 and ulna grade of 6. b) The supine radiograph measured 20.4° (flexibility 38.6%). c) The first in-brace film measured 15.2° (correction rate 54.2%), which yielded a supine correction index of 1.41. d) The curve did not progress with a Cobb angle of 30.7° after brace weaning at skeletal maturity.

1.21, with a sensitivity of 0.591 and a specificity of 0.605. A SCI above 1.21 was significantly predictive of lower risk of progression (OR 0.4 (95% CI 0.251 to 0.955); p = 0.036, chi-squared test). The SCI showed no significant correlation with brace compliance (Pearson's correlation coefficient 0.104; p = 0.192). Figure 2 shows a correlation plot between supine and pre-brace Cobb angle, which yielded an R^2 of 0.527 between the two parameters. An example of the bracing treatment is illustrated in Figure 3.

Discussion

We have shown that high supine flexibility and correction rate are the major determinants of lower risk of curve progression in patients with AIS, after adjusting for maturity and objectively measured brace compliance. By introducing the SCI, we looked at the correction rate with respect to the intrinsic flexibility of individual spines and found that reaching a SCI of 1.21 predicts significantly better brace outcomes.

It is established that a less mature patient and poor brace compliance predict curve progression,[4,5,7] as patients are required to wear the brace longer and are more prone to non-compliance and risk of curve progression. The major unanswered questions for bracing revolve around identifying other morphological factors to prognosticate and improve brace outcomes in cases unexplained by maturity indicators and compliance. Curve flexibility and correction rate are among the predictors with the greatest effect. Ohrt-Nissen et al[11] and Cheung and Cheung[13] found flexibility to be independently predictive of brace outcome using side-bending radiographs and supine radiographs, respectively. It is generally agreed that a correction rate of 30% to 60% is predictive of good brace outcome.[9,10,33] In this study, flexibility is assessed from supine radiographs, which are reliable and easily obtained as they do not require active patient effort in bending. Flexibility assessed in supine radiographs has been shown to predict in-brace correction most accurately compared to prone, sitting bending, and prone bending radiographs.[34] A validated predictive model of correction rate using supine flexibility has also been established for thoracic curves.[13,35]

Our findings on the predictive ability of flexibility and correction rate largely coincide with the literature.[11–13] We have shown that high correction rate and flexibility are significantly predictive of brace success after adjusting for commonly assessed radiological predictors. Substantial effects were found in multivariable logistic regression, with every 1% improvement in flexibility predicting a 5.3% reduction in risk of curve progression, and every 1% improvement in correction rate amounting to a 7.4% reduction in risk of progression. The addition of flexibility and correction rate also significantly improved the model composed of known predictors. The ROC curve analysis yielded acceptable performance with AUC of around 0.7 for both flexibility and correction rate. It is worth noting that the optimal ROC curve cut-off for flexibility (18.1%) is lower than a previous report (28%).[13] This may be due to the patients' awareness of compliance monitoring. Our cohort had a mean brace compliance of 13.1 hours (SD 6.2), which is higher than the mean 12.1 hours' compliance in the Bracing in Adolescent Idiopathic Scoliosis Trial (BrAIST)[2] and the 12.9 hours' compliance threshold for 90% to 93% surgery avoidance rate in BrAIST. This is may reflect the higher brace success rate (78%) in our cohort than reported in BrAIST (72%)[2] and another brace cohort (60%).[13] Nevertheless, the threshold correction rate for good brace outcome in this study (28.8%) matches the lower margin of the 30% to 60% threshold reported in the literature.[9,10,33]

Although correction rate is shown to be prognostic of brace success, it is not possible to produce a high correction rate in brace manufacturing without considering the flexibility of individual spines. Brace fabrication depends on several factors including the flexibility of the spine, patients' tolerance of traction, and strap tightness.[13] Owing to the relationship between in-brace correction and supine flexibility, we propose the SCI as a measure to quantify correction rate with respect to the intrinsic flexibility of the spine. We have shown that reaching an SCI of 1.21 is associated with a 60% reduction in the risk of curve progression. This offers guidance on how much correction should be obtained for a patient with any given supine flexibility to achieve a favourable brace outcome. This may reduce the number of brace modifications and imaging in brace fabrication. As brace fabrication is done by negative casting with traction when the patient is lying in the supine position, correction rate should naturally match supine flexibility.[12] Obtaining an additional 21% correction should be an achievable goal, shown by the fact that the mean correction rate (33.7%) is 1.45 times the mean flexibility (23.2%) in this cohort. It is also interesting to note that SCI shows no association with brace compliance. The optimal cut-off for the SCI requires further validation before it can serve as a clinical guide for bracing. Nevertheless, we have demonstrated that correcting patients beyond their intrinsic supine flexibility does not compromise outcomes and obtaining an additional 21% correction may improve brace outcomes significantly.

To investigate the mechanical effect of bracing, we looked at wedging of the apical vertebra and found that it is predictive of brace outcome in univariable analysis but is not independently predictive of brace outcome when adjusted for known predictors. As curves with large Cobb angles naturally have greater vertebral wedging,[36] this result suggests that the asymmetric loading of forces onto the apical vertebra does not predict poor outcome when the effect of a larger curve magnitude is considered. The change in apical vertebra wedging was significant in patients who progressed but not in stable patients. This may support the idea that bracing can induce a bending moment to nullify the initial asymmetric loading on the apical vertebra,[37] and facilitate bone remodelling to reverse the progressive sequence by the Hueter-Volkmann principle.[37,38] However, apparent changes in vertebral wedging on 2D radiographs may also be due to projection bias caused by vertebral rotation.[13] Studies using 3D stereoradiological reconstruction have shown that rotational correction can improve brace outcome.[18,39] The relative importance of achieving coronal and rotational correction for optimal brace outcome is still under question, and further research efforts should attempt to elucidate the biomechanical effect of bracing in a 3D model.

In our cohort, male patients had a higher rate of progression than female patients, but the effect did not reach statistical significance. Patients with thoracic curves and at premenarche show greater progression, which is largely in agreement with the existing literature.[22,24] Several morphological and clinical predictors were found to have no statistical significance for outcome of bracing. Balance factors on the sagittal and coronal planes (C7-CSVL, truncal shift, and SVA) and shoulder imbalance (T1 tilt and shoulder height difference), which have previously been considered to have an adverse effect on outcomes in the surgical correction of scoliotic spines,[40–43] were found to be irrelevant in the outcome of bracing. BMI is also found to be irrelevant to the result of bracing, contrary to the belief that obese patients experience poor brace correction and outcome.[44]

This study has several limitations. First, this study did not use 3D reconstruction measurements for morphological factors, which may produce inaccurate estimates for certain factors such as vertebral wedging. However, assessment on 2D plain radiographs is generally performed in clinical practice. Axial rotational factors were only measured clinically which is subject to a large margin of error. As a result, in-brace correction in the axial plane and the coupling of changes between planes were not investigated. Also, there is an uneven distribution between the progressed and stable patients, which may undermine the power of the estimates. Nonetheless, this reflects the distribution in the true patient population and therefore results obtained should be of greater external validity.

This is the first prospective study with a respectable sample size to investigate the predictive ability of multiple clinical and radiological morphological factors in braced AIS patients with objectively measured thermal sensor data on brace compliance. We have looked at a comprehensive set of morphological predictors and found them not to be relevant in predicting brace success. We have identified that high supine flexibility and correction rate are independent predictors of good bracing outcome after adjustment for a comprehensive set of factors and have established corresponding cut-offs for optimal outcome. A SCI was established as a clinical guide to optimize brace correction in the coronal plane according to curve flexibility. Further validation is required to establish clinical use for the SCI in optimizing brace outcomes.

Take home message

- Curve progression with brace treatment in patients with adolescent idiopathic scoliosis can be predicted by their curve flexibility and in-brace correction rate.
- A 18.1% supine flexibility and 28.8% correction rate predicts lower risk of curve progression.
- A supine correction index (correction rate/flexibility) greater than 1.21 predicts lower risk of curve progression.

Twitter

Follow J. P. Y. Cheung @jasonpycheung

Supplementary material

Definitions of radiological parameters.

References

1. **Negrini S**, **Donzelli S**, **Aulisa AG**, **et al**. 2016 SOSORT guidelines: orthopaedic and rehabilitation treatment of idiopathic scoliosis during growth. *Scoliosis Spinal Disord*. 2018;13:3.
2. **Weinstein SL**, **Dolan LA**, **Wright JG**, **Dobbs MB**. Effects of bracing in adolescents with idiopathic scoliosis. *N Engl J Med*. 2013;369(16):1512–1521.
3. **Karol LA**, **Virostek D**, **Felton K**, **Wheeler L**. Effect of compliance counseling on brace use and success in patients with adolescent idiopathic scoliosis. *J Bone Joint Surg Am*. 2016;98-A(1):9–14.
4. **Noshchenko A**, **Hoffecker L**, **Lindley EM**, **et al**. Predictors of spine deformity progression in adolescent idiopathic scoliosis: A systematic review with meta-analysis. *World J Orthop*. 2015;6(7):537–558.
5. **van den Bogaart M**, **van Royen BJ**, **Haanstra TM**, **de Kleuver M**, **Faraj SSA**. Predictive factors for brace treatment outcome in adolescent idiopathic scoliosis: a best-evidence synthesis. *Eur Spine J*. 2019;28(3):511–525.
6. **Karol LA**, **Virostek D**, **Felton K**, **Jo C**, **Butler L**. The effect of the Risser stage on bracing outcome in adolescent idiopathic scoliosis. *J Bone Joint Surg Am*. 2016;98-A(15):1253–1259.
7. **Lenz M**, **Oikonomidis S**, **Harland A**, **et al**. Scoliosis and prognosis-a systematic review regarding patient-specific and radiological predictive factors for curve progression. *Eur Spine J*. 2021;30(7):1813–1822.
8. **Vijvermans V**, **Fabry G**, **Nijs J**. Factors determining the final outcome of treatment of idiopathic scoliosis with the Boston brace: a longitudinal study. *J Pediatr Orthop B*. 2004;13(3):143–149.
9. **Goodbody CM**, **Asztalos IB**, **Sankar WN**, **Flynn JM**. It's not just the big kids: both high and low BMI impact bracing success for adolescent idiopathic scoliosis. *J Child Orthop*. 2016;10(5):395–404.
10. **Landauer F**, **Wimmer C**, **Behensky H**. Estimating the final outcome of brace treatment for idiopathic thoracic scoliosis at 6-month follow-up. *Pediatr Rehabil*. 2003;6(3–4):201–207.
11. **Ohrt-Nissen S**, **Hallager DW**, **Gehrchen M**, **Dahl B**. Flexibility predicts curve progression in providence nighttime bracing of patients with adolescent idiopathic scoliosis. *Spine*. 2016;41(22):1724–1730.
12. **Cheung JPY**, **Yiu KKL**, **Vidyadhara S**, **Chan PPY**, **Cheung PWH**, **Mak KC**. Predictability of supine radiographs for determining in-brace correction for adolescent idiopathic scoliosis. *Spine*. 2018;43(14):971–976.
13. **Cheung JPY**, **Cheung PWH**. Supine flexibility predicts curve progression for patients with adolescent idiopathic scoliosis undergoing underarm bracing. *Bone Joint J*. 2020;102-B(2):254–260.
14. **Cheung JPY**, **Chong CHW**, **Cheung PWH**. Underarm bracing for adolescent idiopathic scoliosis leads to flatback deformity: the role of sagittal spinopelvic parameters. *Bone Joint J*. 2019;101-B(11):1370–1378.
15. **Kawasaki S**, **Cheung PWH**, **Shigematsu H**, **et al**. Alternate in-brace and out-of-brace radiographs are recommended to assess brace fitting and curve progression with adolescent idiopathic scoliosis follow-up. *Global Spine J*. 2021.
16. **Catanzano AA**, **Esposito VR**, **Dial BL**, **et al**. Staying ahead of the curve: the use of spinopelvic parameters to predict curve progression and bracing success in adolescent idiopathic scoliosis. *Spine Deform*. 2020;8(6):1213–1222.
17. **Guo J**, **Liu Z**, **Lv F**, **et al**. Pelvic tilt and trunk inclination: new predictive factors in curve progression during the Milwaukee bracing for adolescent idiopathic scoliosis. *Eur Spine J*. 2012;21(10):2050–2058.
18. **Kwan KYH**, **Cheung AKP**, **Koh HY**, **Cheung KMC**. Brace effectiveness is related to 3-Dimensional plane parameters in patients with adolescent idiopathic scoliosis. *J Bone Joint Surg Am*. 2021;103-A(1):37–43.
19. **Thompson RM**, **Hubbard EW**, **Jo CH**, **Virostek D**, **Karol LA**. Brace success is related to curve type in patients with adolescent idiopathic scoliosis. *J Bone Joint Surg Am*. 2017;99-A(11):923–928.
20. **Rowe DE**. The Scoliosis Research Society Brace Manual. The Scoliosis Research Society. http://www.srs.org/UserFiles/file/bracing-manual/section1.pdf (date last accessed 10 February 2022).
21. **Cheung PWH**, **Cheung JPY**. Does the use of Sanders staging and distal radius and ulna classification avoid mismatches in growth assessment with Risser staging alone? *Clin Orthop Relat Res*. 2021;479(11):2516–2530.
22. **Cheung JPY**, **Cheung PWH**, **Samartzis D**, **Luk KDK**. Curve progression in adolescent idiopathic scoliosis does not match skeletal growth. *Clin Orthop Relat Res*. 2018;476(2):429–436.
23. **Luk KDK**, **Saw LB**, **Grozman S**, **Cheung KMC**, **Samartzis D**. Assessment of skeletal maturity in scoliosis patients to determine clinical management: a new classification scheme using distal radius and ulna radiographs. *Spine J*. 2014;14(2):315–325.
24. **Cheung JPY**, **Cheung PWH**, **Yeng WC**, **Chan LCK**. Does curve regression occur during underarm bracing in patients with adolescent idiopathic scoliosis? *Clin Orthop Relat Res*. 2020;478(2):334–345.
25. **Minkara A**, **Bainton N**, **Tanaka M**, **et al**. High risk of mismatch between Sanders and Risser staging in adolescent idiopathic scoliosis: are we guiding treatment using the wrong classification? *J Pediatr Orthop*. 2020;40(2):60–64.
26. **Cheung JPY**, **Cheung PWH**, **Samartzis D**, **Luk KDK**. APSS-ASJ Best Clinical Research Award: predictability of curve progression in adolescent idiopathic scoliosis using the distal radius and ulna classification. *Asian Spine J*. 2018;12(2):202–213.
27. **Cheung JPY**, **Cheung PWH**, **Luk KDK**. When should we wean bracing for adolescent idiopathic scoliosis? *Clin Orthop Relat Res*. 2019;477(9):2145–2157.
28. **Cheung PWH**, **Cheung JPY**. Sanders stage 7b: Using the appearance of the ulnar physis improves decision-making for brace weaning in patients with adolescent idiopathic scoliosis. *Bone Joint J*. 2021;103-B(1):141–147.
29. **Benish BM**, **Smith KJ**, **Schwartz MH**. Validation of a miniature thermochron for monitoring thoracolumbosacral orthosis wear time. *Spine*. 2012;37(4):309–315.
30. **Cheung JPY**, **Cheung PWH**, **Samartzis D**, **Cheung KMC**, **Luk KDK**. The use of the distal radius and ulna classification for the prediction of growth: peak growth spurt and growth cessation. *Bone Joint J*. 2016;98-B(12):1689–1696.
31. **Bursac Z**, **Gauss CH**, **Williams DK**, **Hosmer DW**. Purposeful selection of variables in logistic regression. *Source Code Biol Med*. 2008;3:17.
32. **Pepe MS**. *The Statistical Evaluation of Medical Tests for Classification and Prediction*. Portland, Oregon, USA: Ringgold, Inc, 2005: 85.
33. **Emans JB**, **Kaelin A**, **Bancel P**, **Hall JE**, **Miller ME**. The Boston bracing system for idiopathic scoliosis. Follow-up results in 295 patients. *Spine*. 1986;11(8):792–801.
34. **He C**, **To MKT**, **Cheung JPY**, **et al**. An effective assessment method of spinal flexibility to predict the initial in-orthosis correction on the patients with adolescent idiopathic scoliosis (AIS). *PLoS One*. 2017;12(12):e0190141.
35. **Obid P**, **Yiu KKL**, **Cheung KM**, **Kwan K**, **Ruf M**, **Cheung JPY**. Reliability of rod lengthening, thoracic, and spino-pelvic measurements on biplanar stereoradiography in patients treated with magnetically controlled growing rods. *Spine*. 2018;43(22):1579–1585.
36. **Labrom FR**, **Izatt MT**, **Contractor P**, **et al**. Sequential MRI reveals vertebral body wedging significantly contributes to coronal plane deformity progression in adolescent idiopathic scoliosis during growth. *Spine Deform*. 2020;8(5):901–910.
37. **Clin J**, **Aubin C-É**, **Sangole A**, **Labelle H**, **Parent S**. Correlation between immediate in-brace correction and biomechanical effectiveness of brace treatment in adolescent idiopathic scoliosis. *Spine (Phila Pa 1976)*. 2010;35(18):1706–1713.
38. **Castro FP**. Adolescent idiopathic scoliosis, bracing, and the Hueter-Volkmann principle. *Spine J*. 2003;3(3):180–185.
39. **Almansour H**, **Pepke W**, **Bruckner T**, **Diebo BG**, **Akbar M**. Three-dimensional analysis of initial brace correction in the setting of adolescent idiopathic scoliosis. *J Clin Med*. 2019;8(11):E1804.
40. **Smyrnis PN**, **Sekouris N**, **Papadopoulos G**. Surgical assessment of the proximal thoracic curve in adolescent idiopathic scoliosis. *Eur Spine J*. 2009;18(4):522–530.
41. **Zang L**, **Fan N**, **Hai Y**, **et al**. Evaluation of the predictors of postoperative aggravation of shoulder imbalance in severe and rigid thoracic or thoracolumbar scoliosis. *Eur Spine J*. 2016;25(10):3353–3365.
42. **Anari JB**, **Tatad A**, **Cahill PJ**, **Flynn JM**, **Harms Study Group**. The impact of posterior spinal fusion (PSF) on coronal balance in adolescent idiopathic scoliosis (AIS): a new classification and trends in the postoperative period. *J Pediatr Orthop*. 2020;40(9):e788–e793.
43. **Hwang CJ**, **Lee CS**, **Kim H**, **Lee DH**, **Cho JH**. Spontaneous correction of coronal imbalance after selective thoracolumbar-lumbar fusion in patients with Lenke-5C adolescent idiopathic scoliosis. *Spine J*. 2018;18(10):1822–1828.
44. **Karol LA**, **Wingfield JJ**, **Virostek D**, **Felton K**, **Jo C**. The influence of body habitus on documented brace wear and progression in adolescents with idiopathic scoliosis. *J Pediatr Orthop*. 2020;40(3):e171–e175.

Author information:
L. P. K. Wong, MRes Candidate
P. W. H. Cheung, BDSc (Hons), Senior Research Assistant
J. P. Y. Cheung, MBBS, MMedSc, MS, PDipMDPath, MD, MEd, FRCSEd, FHKCOS, FHKAM, Clinical Associate Professor and Head of Department
Department of Orthopaedics and Traumatology, University of Hong Kong, Hong Kong, China.

Author contributions:
L. P. K. Wong: Methodology, Investigation, Data curation, Formal analysis, Validation, Visualization, Writing – original draft.
P. W. H. Cheung: Methodology, Supervision, Software, Investigation, Data curation, Formal analysis, Validation, Visualization, Writing – review & editing.
J. P. Y. Cheung: Conceptualization, Methodology, Project administration, Funding acquisition, Supervision, Resources, Software, Investigation, Data curation, Formal analysis, Validation, Visualization, Writing – review & editing.

Funding statement:
The authors disclose receipt of the following financial or material support for the research, authorship, and/or publication of this article: RGC Research Impact Fund (R5017-18F).

Acknowledgements:
We thank Lawrence Chan (LC), Vincent Yeng (VY) and Ng Pun-Fai (NPF) for their orthotic expertise in managing these patients.

Ethical review statement:
Ethics was approved by the Institutional Review Board of the University of Hong Kong / Hospital Authority Hong Kong West Cluster (HKU/HA HKW IRB): UW 15-596.

Open access funding
Open access funding was supported by the RGC Research Impact Fund (R5017-18F).

This article was primary edited by A. C. Ross and G. Scott.