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The effect of brace treatment history on bone density in preoperative patients with adolescent idiopathic scoliosis (AIS) assessed by vertebral bone quality (VBQ) score: a retrospective propensity score-matched analysis

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Abstract

Introduction Adolescent idiopathic scoliosis (AIS), a prevalent condition among teenagers, is often accompanied by osteopenia. However, the impact of brace treatment on bone density in AIS patients remains a matter of debate. The Vertebral bone quality (VBQ) score, derived from MRI signal intensity, has been shown to correlate with bone mineral density (BMD). Yet, no studies to date have drawn comparisons between VBQ scores in preoperative AIS patients who had brace treatment history and those who have not received brace treatment.

Objective This study aims to elucidate the influence of brace treatment on bone density in AIS patients using VBQ score.

Methods A retrospective analysis was conducted on 243 AIS patients, each with Cobb angles ranging from 50–70°, who had undergone preoperative MRI scans. The patients were segregated into two cohorts: those who received brace treatment ($n = 174$) and those who did not ($n = 69$). Through propensity score matching, a total of 53 matched pairs were selected for further analysis. VBQ scores were extracted from T1-weighted MRI scans.

Results Post-matching, no significant baseline discrepancies were observed between the two groups. Interestingly, brace-treated patients exhibited lower average VBQ scores than their non-brace-treated counterparts (2.43 ± 0.11 vs. 2.55 ± 0.12 , $p < 0.01$), suggesting a higher bone density. Furthermore, a negative correlation was observed between VBQ scores and the duration of brace usage ($R^2 = 0.3853$, $p < 0.01$).

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Conclusion Brace treatment may potentially enhance bone density in AIS patients by mitigating vertebral fat infiltration. The utilization of VBQ scores presents an alternative, potentially robust approach to assessing bone quality.

Keywords Adolescent idiopathic scoliosis, Vertebral bone quality score, Brace, BMD

Introduction

AIS is a three-dimensional spinal deformity with a prevalence of 2–4% in the general population [1]. The etiology of AIS is unknown, but it is likely multifactorial, involving genetic, environmental, hormonal, and biomechanical factors [2, 3]. Brace treatment is one of the non-surgical options for AIS patients with mild to moderate curves (20–40°) or progressive curves ($\geq 5^\circ$ increase in 6 months) [4, 5]. Brace treatment involves wearing a rigid or semi-rigid device that applies corrective forces to the spine and reduces the mechanical load on the vertebrae. The effectiveness of brace treatment depends on several factors, such as curve type, magnitude, flexibility, skeletal maturity, and compliance [4, 6].

However, the majority of AIS patients were reported to be osteopenia [7–11]. The effect of brace treatment on bone density in AIS patients was controversial. Most studies have found no significant difference in BMD between brace-treated and non-brace-treated AIS patients [12, 13], while others have reported lower BMD in brace-treated patients [14] or higher BMD in brace-treated patients [15]. The discrepancy may be due to different methods of measuring BMD. BMD measurements by dual-energy X-ray absorptiometry (DXA) may not reflect the true bone quality of AIS patients, as they are influenced by factors such as spinal rotation and vertebral wedging [16, 17].

T1-weighted MRI-measured bone marrow adipose tissue signal intensity has been validated to exhibit a significant negative correlation with bone mineral density as assessed by DXA [18]. In light of these findings, a novel MRI-based vertebral bone quality (VBQ) score has been proposed to evaluate bone mineral density [19]. The VBQ score has demonstrated a strong correlation with BMD measurements obtained via DXA. An elevated VBQ score could potentially indicate increased fat infiltration within the vertebral body, suggestive of osteoporotic bone characterized by trabecular atrophy and local adipocyte replacement [19]. In addition, Chen et al. established the VBQ cut-off scores for diagnosing osteopenia and osteoporosis as 2.6 and 2.8, respectively [20]. Furthermore, Aynaszyan et al. found that the VBQ score is influenced by HDL levels and exhibits a relationship with BMI [21]. However, to the best of our knowledge, no known studies have compared VBQ scores between brace-treated and non-brace-treated preoperative AIS patients. Hence, this study aimed to evaluate the influence of brace treatment on bone quality in AIS patients by using the VBQ score.

Methods

Patient selection

A retrospective study design was conducted to investigate the effect of brace treatment on bone density in AIS patients using VBQ score. In our department, preoperative MRI examinations were only administered to patients with AIS who require surgical intervention. We collected inpatient records from February 2012 to March 2018 in our department. To ensure a homogeneous baseline for this study, our analysis solely focused on AIS patients with moderate scoliosis (Cobb angle ranging from 50 to 70 degrees). The inclusion criteria for this study were as follows: (1) the age of the patients ranged from 11 to 18 years; (2) possession of a preoperative T1-weighted non-contrast-enhanced MRI scan without any prior lumbar instrumentation. And the exclusion criteria included: 1) patients who underwent surgical intervention for conditions other than AIS, such as malignancies, infections, trauma, or diagnoses of chronic liver disease, renal failure, and metabolic bone diseases; 2) patients diagnosed with other types of scoliosis, such as neuromuscular, congenital, or neurofibromatosis-associated; 3) patients with incomplete medical records. All procedures and methods were approved by the research ethics committee of the West China hospital and provided informed consent. All protocols were conducted in accordance with the research principles set forth in the Declaration of Helsinki.

Data collection

We collected patient demographics and general characteristics, such as age, sex, weight, height, body mass index (BMI) and brace treatment history. Additionally, we also measured the Cobb angle of main curve in standing full-length posteroanterior plain radiographs and the VBQ scores in T1-weighted MRI. One week after one author assessed the parameters, he repeated the measurements to evaluate intraobserver reliability. Another author also measured the parameters to assess interobserver reliability. The intraclass correlation coefficients (ICCs) for intraobserver and interobserver reliability were 0.891 and 0.903, respectively.

Brace treatment

According to previous literature [22], AIS patients who had undergone brace treatment included in this study were provided with a Chêneau-type brace, which was prescribed and regularly monitored by an experienced physician. The recommended wearing schedule for the

brace during the first year was 21–23 h per day. Compliance with brace usage and the maximum daily wearing time achieved were assessed by the treatment team and recorded. As patients progressed to Risser stage 4, the daily wearing time was gradually reduced by two hours per month. Once the wearing time reached 10–12 h per day, the brace was transitioned to nighttime use only for a period of 6 months before discontinuation of brace treatment. If the patient's Cobb angle reached the surgical threshold during follow-up, it was recommended that the patient underwent inpatient surgical treatment.

VBQ score calculation

Building upon prior research [19], the VBQ score was assessed based on the signal intensity (SI) extracted from non-contrast-enhanced T1-weighted MRI scans of the midsagittal plane of the lumbar spine. An initial step

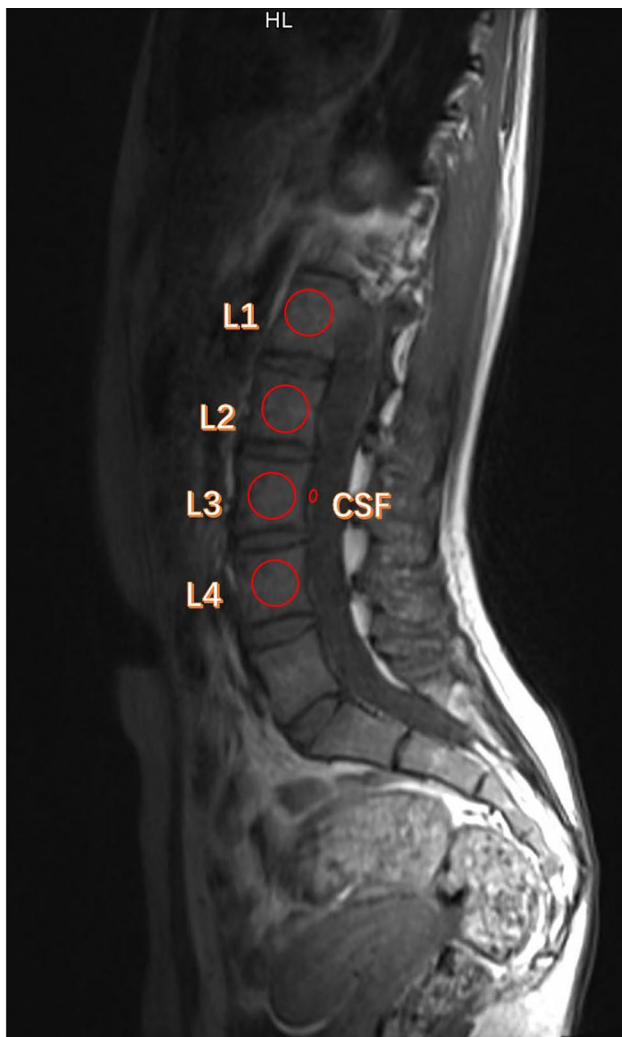


Fig. 1 The signal intensity of regions of interest (red circles) utilized for the computation of VBQ score is demonstrated through sagittal non-contrast-enhanced T1-weighted MRI

involved manually positioning a region of interest (ROI) within the medullary bone of the L1–L4 vertebral bodies and within the cerebrospinal fluid (CSF) at the L3 level (Fig. 1).

To exclude cortical bone influence, a concentric ROI was strategically positioned approximately 3 mm from the vertebral body's perimeter. Special attention was aimed at maintaining ROI size consistency to reduce measurement variability. Following this, SI values for the L1–L4 vertebral bodies were computed and subsequently normalized by dividing these by the mean SI value of the CSF at L3.

$$VBQ\ Score = \frac{SI_{L1-L4}}{SI_{CSF}}$$

Statistical analysis

All analyses were performed using SPSS 23.0 (SPSS, IBM Analytics, New York, USA) and the figures were created by GraphPad Prism version 9.3.0 (GraphPad Software, San Diego, California USA). Continuous variables were reported as mean ± standard deviation (SD), and differences between groups were assessed using Student's t-test for statistical significance. Propensity score matching (PSM) analysis used the greedy nearest neighbor method for data matching, with ratio=1:1 and caliper=0.04. Age, sex, height, weight, BMI, Cobb angle, curve types and Risser sign were included as confounding variables in the matching process. $P < 0.05$ was considered statistically significant.

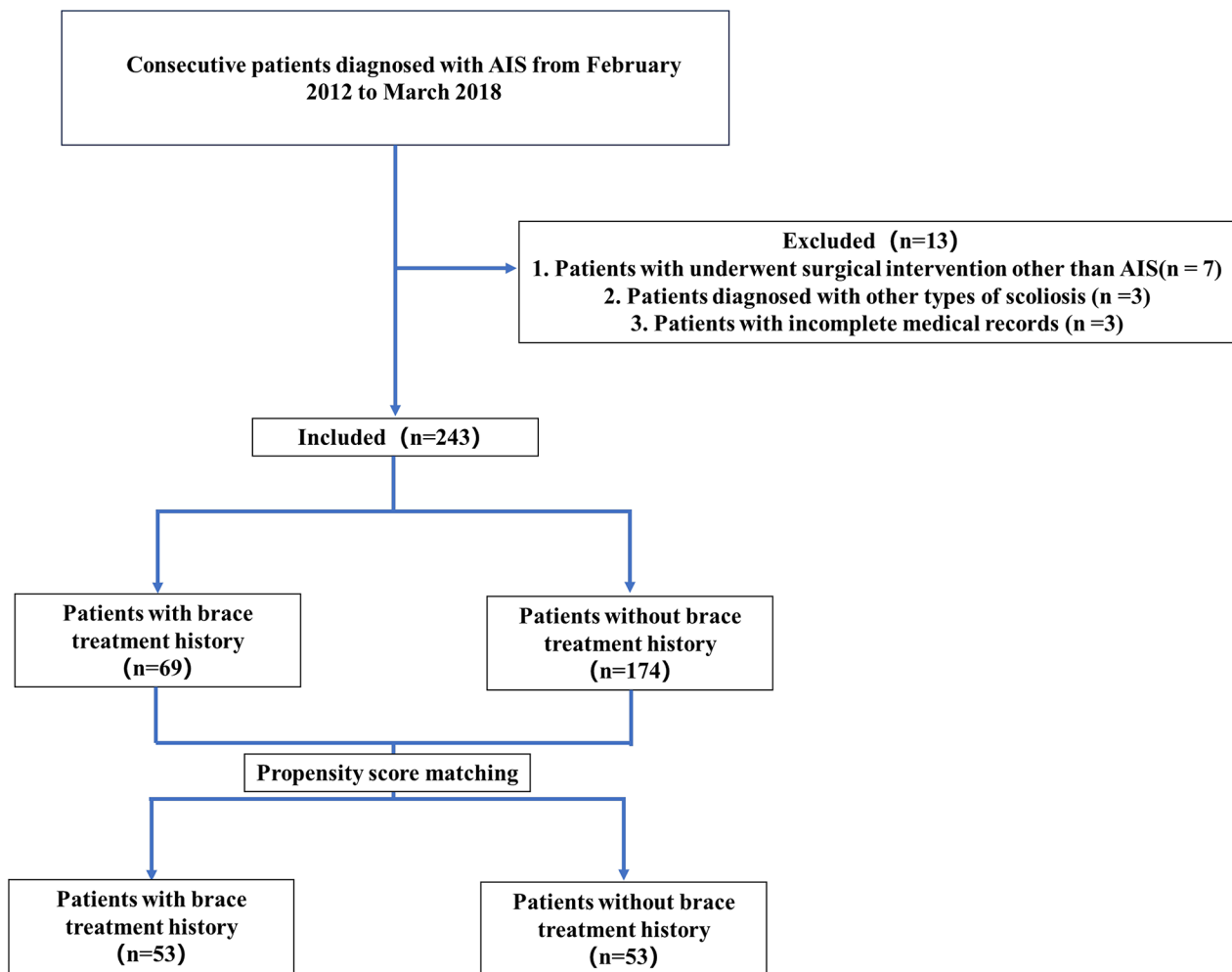
Results

Study population

A total of 256 patients diagnosed with AIS were initially enrolled in the study. Of these, 7 patients who underwent surgical intervention for conditions other than AIS, 3 patients diagnosed with other types of scoliosis and 3 patients with incomplete medical records were excluded. This left a total of 243 patients for analysis, including 42 males and 201 females with a mean age of 14.1 ± 2.2 years (range 11–18 years). Among the enrolled AIS patients, 69 had not received brace treatment prior to the study. After propensity score matching, 53 matched pairs of patients were selected from each group for further analysis (Fig. 2).

Comparison of general characteristic between patients with and without brace treatment history

The characteristics of the patients with and without brace treatment history before propensity score matching were summarized in Table 1. There were no significant differences between the non-brace treated group and the brace treated group in terms of age, sex distribution,



Figs. 2 The flow diagram of patients through this study

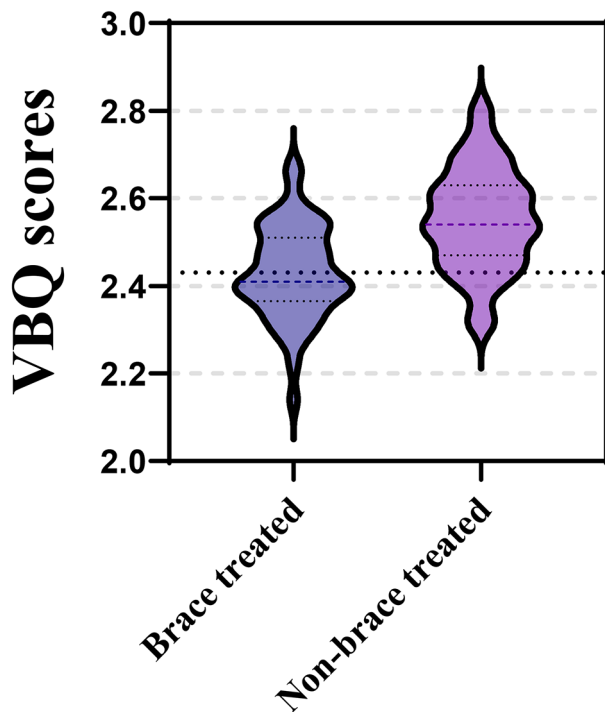
Table 1 Characteristics of the patients with and without brace treatment history before propensity score matching

| Variable | Non-brace treated group (N= 69) | Brace treated group (N= 174) | P value |
|-----------------------------|---------------------------------|------------------------------|---------|
| Age(years) | 14.3 ± 2.1 | 14.1 ± 2.3 | 0.54 |
| Height(m) | 1.57 ± 0.10 | 1.58 ± 0.09 | 0.39 |
| Sex | | | |
| Male | 11(15.9%) | 31(17.8%) | |
| Female | 58(84.1%) | 145(83.2%) | 0.85 |
| Weight(kg) | 49.0 ± 5.3 | 47.40 ± 4.3 | 0.02* |
| BMI(Kg/m ²) | 20.1 ± 3.4 | 19.1 ± 2.7 | 0.01* |
| Curve types | | | |
| Thoracic | 37(53.6%) | 90(51.7%) | |
| Double | 20(29.0%) | 61(35.1%) | |
| Thoracolumbar/lumbar | 12(2.4%) | 23(13.2%) | 0.55 |
| Risser sign | 2.6 ± 1.3 | 2.6 ± 1.2 | 0.69 |
| Cobb angle of main curve(°) | 58.2 ± 8.8 | 57.5 ± 5.9 | 0.46 |

BMI, Body Mass Index. * P < 0.05

Table 2 Characteristics of the patients with and without brace treatment history after propensity score matching

| Variable | Non-brace treated group (N=53) | Brace treated group (N=53) | P value |
|-----------------------------|--------------------------------|----------------------------|---------|
| Age(years) | 14.2±2.0 | 14.3±2.5 | 1.00 |
| Height(m) | 1.59±0.09 | 1.59±0.10 | 1.00 |
| Sex | | | |
| Male | 10(18.9%) | 9(17.0%) | |
| Female | 43(81.1%) | 44(83.0%) | 1.00 |
| Weight(kg) | 48.5±5.3 | 48.7±4.6 | 1.00 |
| BMI(Kg/m ²) | 19.3±2.9 | 19.7±2.9 | 1.00 |
| Curve types | | | |
| Thoracic | 28(52.8%) | 31(58.5%) | |
| Double | 16(30.2%) | 14(26.4%) | |
| Thoracolumbar/lumbar | 9(17.0%) | 8(15.1%) | 0.84 |
| Risser sign | 2.7±1.3 | 2.7±1.2 | 1.00 |
| Cobb angle of main curve(°) | 59.4±6.2 | 57.8±6.4 | 0.11 |

**Fig. 3** Violin plot illustrating the VBQ scores within the brace treated and non-brace treated groups

height, curve types, risser sign and cobb angle of main curve. However, significant differences were observed in weight and BMI between the two groups. The average weight of the patients in the non-brace treated group was significantly higher than that in the brace treated group (49.0 ± 5.3 vs. 47.40 ± 4.3 , $P=0.02$). Likewise, the average BMI of the patients in the non-brace treated group was also higher than that in the brace treated group (20.1 ± 3.4 vs. 19.1 ± 2.7 , $P=0.01$). In order to mitigate the effects of baseline imbalances, we conducted propensity score matching between the two groups. After propensity score matching, no significant differences were observed in

all the baseline characteristics between the two groups (Table 2).

VBQ scores between patients with and without brace treatment history

After conducting a propensity score-matching procedure, we compared the VBQ scores between the brace treated group and the non-brace treated group. As shown in Fig. 3, it was observed that the brace treated group exhibited significantly lower VBQ scores compared to the non-brace-treated group (2.43 ± 0.11 vs. 2.55 ± 0.12 , $P<0.01$).

Discussion

In this study, we investigated the effect of brace treatment on bone density in preoperative AIS patients by using VBQ score, which is a novel method to assess vertebral bone quality based on MRI signal intensity. This is the first study to utilize the VBQ score to explore the impact of bracing on bone quality in AIS patients undergoing surgery.

We found that patients with brace treatment had significantly lower weight and BMI than those without brace treatment at baseline before propensity score matching, which might be explained by the fact that early detection of external bodily deformities tends to be challenging in overweight patients. To eliminate the confounding effect of BMI, we matched the two groups by propensity score and obtained a 1:1 matched cohort. After matching, we observed that patients with brace treatment still had significantly lower VBQ score than those without brace treatment, suggesting that they might have better bone quality. This finding was contrary to most previous studies using DXA to measure BMD in brace-treated AIS patients, which showed no difference in BMD between braced and non-braced groups [12, 13]. Interestingly, as Chen et al. suggested VBQ cut-off values of 2.6 for osteopenia diagnosis and 2.8 for osteoporosis [20], the

percentage of patients with VBQ score above 2.6 was markedly lower in the brace-treated group compared to the non-brace treated group in our study as shown in Fig. 3, which indicated a potential association between brace treatment and bone quality in AIS patients.

The divergence in our findings from those of prior research may be attributed to the distinct methodologies employed to evaluate bone quality. DXA quantified bone mineral amount to yield a two-dimensional areal bone mineral density (aBMD) rather than a true three-dimensional volumetric bone mineral density (vBMD) [17]. This measurement was susceptible to alterations resulting from spinal rotation and vertebral wedging in AIS. Furthermore, DXA lacked the capacity to elucidate the microarchitecture or composition of bone tissue [23]. In contrast, MRI can furnish data on fat content and its distribution within the vertebral body, which has been corroborated to closely align with the BMD. Prior investigations have suggested a connection between fat infiltration in bone marrow and diminished bone formation, augmented bone resorption, and compromised bone mechanical properties [24]. The employment of VBQ score as a bone density indicator offered several benefits over DXA in AIS. Primarily, the VBQ score was extrapolated from MRI, which could spare patients from ionizing radiation exposure and boasted a higher spatial resolution than DXA. Secondly, the VBQ score effectively mitigated potential confounding factors, such as vertebral rotation and wedging, as well as posterior soft tissue interference like adipose tissue, which DXA was susceptible to, due to its inherent two-dimensional measurement limitations [17]. Lastly, the VBQ score could be conveniently computed from existing MRI images, obviating the need for additional scans or specialized software.

While dynamic hyperextension brace was reported to improve BMD in postmenopausal osteoporotic women [15], no study before showed that the brace might help prevent osteopenia in AIS patients. We were the first study to report the brace treatment history may influence the VBQ score in AIS patients undergoing surgery. The possible mechanism for our findings was that brace treatment provides external mechanical stress to the spine, which may stimulate bone formation and calcium deposition in patients with AIS [25]. Previous studies have shown that mechanical stress can activate osteogenic genes such as OCN and OPN, which are involved in bone matrix synthesis and mineralization [26–28]. Moreover, mechanical stress can also inhibit adipogenic genes such as PPAR γ and C/EBP α , which are responsible for fat differentiation and accumulation in bone marrow [29]. Therefore, brace treatment may modulate the balance between osteogenesis and adipogenesis in the vertebrae of patients with AIS.

Our study had some limitations that need to be addressed. Firstly, our study was a single-center, retrospective investigation with a relatively limited sample size, which may limit the statistical power and definitive conclusions on the cause-effect relationship between brace treatment and VBQ scores. And our findings were limited to the analyzed AIS population undergoing surgery. Second, we did not include other serological indicators, such as 25-hydroxy vitamin D and alkaline phosphatase (ALP), which are emblematic of osteogenic capability. Third, given that our department only conducted MRI examinations for hospitalized patients, we only measured VBQ score at one time point before surgery, and did not have longitudinal data on the changes of VBQ score. Thus, more detailed and controlled studies with more patients and a longitudinal follow-up period need to be conducted in the future.

Conclusion

In conclusion, our study demonstrated significantly lower VBQ scores in brace-treated AIS patients compared to non-brace-treated patients undergoing surgery. These findings suggest that brace treatment may have an impact on VBQ in AIS patients. However, the exact mechanisms underlying this relationship remain unclear. Further longitudinal studies with larger sample sizes may be required to elucidate the potential mechanisms and quantify the impact of brace treatment on bone quality in AIS patients.

Abbreviations

| | |
|-----|----------------------------------|
| AIS | Adolescent idiopathic scoliosis |
| VBQ | Vertebral bone quality |
| BMD | Bone mineral density |
| DXA | Dual-energy X-ray absorptiometry |
| BMI | Body mass index |

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Not applicable.

Author contributions

JW and CZ conceived and designed the study, as well as drafted the initial manuscript. YA, YH, QC, and HD performed the preliminary analyses. GF, LL, and YS critically reviewed and revised the manuscript to ensure significant intellectual content. All authors have approved the final manuscript for submission and accept responsibility for all aspects of the work.

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Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

This study was approved by the Ethics Committee of the West China Hospital (Approval No. 2019852). All of the participants (if subjects were under 16, from a parent and/or legal guardian) involved in the study provided their electronic written informed consent before being surveyed.

Consent for publication

Written informed consent was obtained from all patients for the publication of any accompanying images and videos.

Competing interests

The authors declare no competing interests.

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References

- Galbusera F, Cina A, Panico M, Bassani T. The importance of curve severity, type and instrumentation strategy in the surgical correction of adolescent idiopathic scoliosis: an in silico clinical trial on 64 cases. *Sci Rep*. 2021;11(1):1799.
- Marya S, Tambe AD, Millner PA, Tsirikos AI. Adolescent idiopathic scoliosis: a review of aetiological theories of a multifactorial disease. *bone Joint J*. 2022;104-b(8):915–21.
- Kikanloo SR, Tarpada SP, Cho W. Etiology of adolescent idiopathic scoliosis: a Literature Review. *Asian Spine J*. 2019;13(3):519–26.
- Negrini S, Minozzi S, Bettany-Saltikov J, Chockalingam N, Grivas TB, Kotwicki T et al. Braces for idiopathic scoliosis in adolescents. *Cochrane Database Syst Rev*. 2015(6):Cd006850.
- Hawary RE, Zaaroor-Regev D, Floman Y, Lonner BS, Alkhalife YI, Betz RR. Brace treatment in adolescent idiopathic scoliosis: risk factors for failure—a literature review. *Spine Journal: Official J North Am Spine Soc*. 2019;19(12):1917–25.
- Ali A, Fontanari V, Fontana M, Schmölz W. Spinal deformities and Advancement in Corrective Orthoses. *Bioeng (Basel Switzerland)*. 2020;8(1).
- Yu WS, Chan KY, Yu FW, Yeung HY, Ng BK, Lee KM, et al. Abnormal bone quality versus low bone mineral density in adolescent idiopathic scoliosis: a case-control study with in vivo high-resolution peripheral quantitative computed tomography. *Spine Journal: Official J North Am Spine Soc*. 2013;13(11):1493–9.
- Nishida M, Yagi M, Suzuki S, Takahashi Y, Nori S, Tsuji O et al. Persistent low bone mineral density in adolescent idiopathic scoliosis: a longitudinal study. *J Orthop Science: Official J Japanese Orthop Association*. 2022.
- Li XF, Li H, Liu ZD, Dai LY. Low bone mineral status in adolescent idiopathic scoliosis. *European spine journal: official publication of the European Spine Society, the European Spinal Deformity Society, and the European section of the cervical. Spine Res Soc*. 2008;17(11):1431–40.
- Li X, Hung VWY, Yu FWP, Hung ALH, Ng BKW, Cheng JCY, et al. Persistent low-normal bone mineral density in adolescent idiopathic scoliosis with different curve severity: a longitudinal study from presentation to beyond skeletal maturity and peak bone mass. *Bone*. 2020;133:115217.
- Lam TP, Yang G, Pang H, Yip B, Lee W, Hung A, et al. A six years longitudinal cohort study on the changes in bone density and bone quality up to peak bone mass in adolescent idiopathic scoliosis (AIS) with and without 2 years of calcium and Vit-D supplementation. *Stud Health Technol Inform*. 2021;280:31–4.
- Pourabbas Tahvildari B, Erfani MA, Nouraei H, Sadeghian M. Evaluation of bone mineral status in adolescent idiopathic scoliosis. *Clin Orthop Surg*. 2014;6(2):180–4.
- Ohashi M, Watanabe K, Hirano T, Hasegawa K, Katsumi K, Shoji H, et al. Long-term impacts of Brace Treatment for adolescent idiopathic scoliosis on body composition, Paraspinal Muscle Morphology, and bone Mineral Density. *Spine*. 2019;44(18):E1075–82.
- Balioglu M, Albayrak A, Atici Y, Kargin D, Tacal MT, Kaygusuz MA, et al. Does the use of Brace Treatment have an Effect on Bone Mineral density in adolescent idiopathic scoliosis patients? *J Turkish Spinal Surg*. 2014;25:25–31.
- Shariatzadeh H, Modaghegh BS, Mirzaei A. The Effect of Dynamic Hyperextension Brace on osteoporosis and hyperkyphosis reduction in postmenopausal osteoporotic women. *Archives bone Joint Surg*. 2017;5(3):181–5.
- Cheuk KY, Hu Y, Tam EMS, Shi L, Yu FWP, Hung VWY, et al. Bone measurements at multiple skeletal sites in adolescent idiopathic scoliosis—an in vivo correlation study using DXA, HR-pQCT and QCT. *Archives Osteoporos*. 2019;14(1):70.
- Golding PH. Dual-energy X-ray absorptiometry (DXA) to measure bone mineral density (BMD) for diagnosis of osteoporosis - experimental data from artificial vertebrae confirms significant dependence on bone size. *Bone Rep*. 2022;17:101607.
- Shen W, Scherzer R, Gantz M, Chen J, Punyanitya M, Lewis CE, et al. Relationship between MRI-measured bone marrow adipose tissue and hip and spine bone mineral density in African-American and caucasian participants: the CARDIA study. *J Clin Endocrinol Metab*. 2012;97(4):1337–46.
- Ehresman J, Pennington Z, Schilling A, Lubelski D, Ahmed AK, Cottrill E, et al. Novel MRI-based score for assessment of bone density in operative spine patients. *Spine Journal: Official J North Am Spine Soc*. 2020;20(4):556–62.
- Chen Z, Lei F, Ye F, Yuan H, Li S, Feng D. MRI-based vertebral bone quality score for the assessment of osteoporosis in patients undergoing surgery for lumbar degenerative diseases. *J Orthop Surg Res*. 2023;18(1):257.
- Aynaszyn S, Devia LG, Udoyo IF, Badve SA, DelSole EM. Patient physiology influences the MRI-based vertebral bone quality score. *Spine Journal: Official J North Am Spine Soc*. 2022;22(11):1866–74.
- Kuru Çolak T, Akçay B, Apti A, Çolak İ. The effectiveness of the Schroth Best Practice Program and Chêneau-Type Brace Treatment in adolescent idiopathic scoliosis: long-term Follow-Up evaluation results. *Children (Basel, Switzerland)*. 2023;10(2).
- Mussawy H, Ferrari G, Schmidt FN, Schmidt T, Rolvien T, Hischke S, et al. Changes in cortical microarchitecture are independent of areal bone mineral density in patients with fragility fractures. *Injury*. 2017;48(11):2461–5.
- Al Saedi A, Chen L, Phu S, Vogrin S, Miao D, Ferland G, et al. Age-Related increases in Marrow Fat volumes have Regional impacts on bone cell numbers and structure. *Calcif Tissue Int*. 2020;107(2):126–34.
- Liu P, Tu J, Wang W, Li Z, Li Y, Yu X, et al. Effects of mechanical stress stimulation on function and expression mechanism of Osteoblasts. *Front Bioeng Biotechnol*. 2022;10:830722.
- Wang L, You X, Zhang L, Zhang C, Zou W. Mechanical regulation of bone remodeling. *Bone Res*. 2022;10(1):16.
- Yourek G, McCormick S, Mao J, Reilly G. Shear stress induces osteogenic differentiation of human mesenchymal stem cells. *Regen Med*. 2010;5:713–24.
- Chang Y, Shao Y, Liu Y, Xia R, Tong Z, Zhang J, et al. Mechanical strain promotes osteogenic differentiation of mesenchymal stem cells on TiO₂ nanotubes substrate. *Biochem Biophys Res Commun*. 2019;511(4):840–6.
- Li R, Liang L, Dou Y, Huang Z, Mo H, Wang Y, et al. Mechanical strain regulates osteogenic and adipogenic differentiation of bone marrow mesenchymal stem cells. *Biomed Res Int*. 2015;2015:873251.

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