

RESEARCH ARTICLE

Open Access



# Can preoperative magnetic resonance imaging be used for sagittal kyphotic flexibility assessment in patients with kyphosis secondary to symptomatic old osteoporotic thoracolumbar fracture?

Kangkang Wang<sup>1,2</sup>, Feng Zhang<sup>1,2</sup>, Yunlei Zhai<sup>1,2</sup>, Wei Zhang<sup>1,2</sup>, Wen Yin<sup>1,2</sup>, Lele Sun<sup>1,2</sup>, Xilong Cui<sup>3\*</sup> and Haiyang Yu<sup>1,2,3\*</sup>

## Abstract

**Objective** This study aimed to investigate whether preoperative magnetic resonance imaging (MRI) can be used for sagittal kyphotic (SK) flexibility assessment in patients with kyphosis secondary to symptomatic old osteoporotic thoracolumbar fracture (so-OTLF).

**Methods** The authors evaluated the radiographic data of patients with kyphosis secondary to so-OTLF. All patients underwent posterior corrective fusion surgery in the hospital. Spinal sagittal parameters were measured on standing radiographs preoperatively. The regional kyphosis angle (RKA) was also measured on preoperative supine MRI and intraoperative prone radiographs on the surgical frame. The SK flexibility in patients with kyphosis secondary to so-OTLF was defined as the difference from the RKA measured on the standing radiographs to that measured on the intraoperative prone radiographs or preoperative supine MRI. The difference and the correlation between the SK flexibility measured by these two methods were compared and analyzed.

**Results** Thirty-seven patients were included. The RKA measured on standing radiographs, supine MRI, and intraoperative prone radiographs were 48.0°, 34.4°, and 32.0°, respectively. Compared with the RKA measured in standing position, the RKA measured on supine MRI decreased by 13.6° (95% confidence interval 11.4°–15.8°), whereas that measured on intraoperative prone radiographs decreased by 16.1° (95% confidence interval 13.7°–18.5°). A linear correlation existed between the SK flexibility measured on supine MRI and that measured on intraoperative prone radiographs, with a mean difference of 2.4° ( $R^2 = 0.912$ ,  $p < 0.001$ ).

**Conclusion** The degree of regional kyphosis deformity was reduced by self-reduction of the intraoperative surgical frame. With a predictive value similar to an intraoperative prone radiograph, preoperative supine MRI can be used for SK flexibility assessment in patients with kyphosis secondary to so-OTLF. The ability to predict the intraoperative

\*Correspondence:

Xilong Cui  
cuixilong.wang@163.com  
Haiyang Yu  
fy.yhy@163.com

Full list of author information is available at the end of the article



© The Author(s) 2023. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>. The Creative Commons Public Domain Dedication waiver (<http://creativecommons.org/publicdomain/zero/1.0/>) applies to the data made available in this article, unless otherwise stated in a credit line to the data.

degree of regional kyphosis deformity with positioning before an operation may help with surgical planning and patient counseling regarding expectations and risks of surgery.

**Keywords** Regional kyphosis angle, Symptomatic old osteoporotic thoracolumbar fracture, Kyphosis, Sagittal kyphotic flexibility, Magnetic resonance imaging

## Introduction

Given the accelerating aging process of the population, kyphosis secondary to osteoporotic spinal fracture has become a common type of deformity in clinical practice, posing a threat to the physical and mental health of middle-aged and elderly people [1]. Although conservative treatments are effective in temporarily reducing chronic back pain, some individuals with remarkable sagittal imbalance or neurological deficiencies may still need to undergo surgery [2–5]. Despite the fact that the use of ultrasound bone scalpel, spinal cord monitor, and other medical equipment has improved the safety of surgical treatment, these patients often have complications, i.e., circulatory, respiratory, endocrine, and other systemic diseases. Osteotomy for them is still a great challenge. Only the radiographic parameters of the standing spine full-length radiographs are used to create the surgical plan; this approach carries potential risks, such as significant trauma, increased blood loss, and extended recovery times; some patients may even lose the chance to avail of a surgical cure [6].

In addition to the size of the regional kyphosis angle (RKA) in the standing position and the presence or absence of sagittal imbalance, the surgical plan is also chosen based on the flexibility of the sagittal kyphosis [2, 7]. The kyphotic angle that needs to be corrected during the surgery for flexible kyphotic deformity can be reduced by the self-reduction of the intraoperative position of the surgical frame. However, for rigid kyphosis deformity, the poor mobility of the deformed vertebral body and the adjacent intervertebral space indicate that attempting to restore satisfactory degree correction and sagittal balance without a three-column osteotomy is unrealistic [8–10].

Overextension and overflexion dynamic radiographs are usually used to evaluate the stability of the lumbar intervertebral space. However, the dynamic X-ray film underestimates the reducibility of the kyphosis deformity in these patients. The reason is that the increase in muscle activity and pain of patients during dynamic view shooting prevents some patients from completing movements independently, and these factors are neutralized when patients lie down [11]. We hypothesized that the duration of patient's lying position during preoperative MRI examination was long enough to eliminate such factors as gravity, intractable lumbodorsal

pain, and nerve traction pain caused by lumbar spinal stenosis, so as to reduce the compensatory angle that can be reduced and obtain a more realistic kyphosis angle. Although various authors have analyzed the predictive value of supine MRI in predicting TK and LL flexibility for adult spinal deformity, there are few reports about the predictive role of MRI in SK kyphosis flexibility assessment in patients with kyphosis secondary to so-OTLF [12, 13].

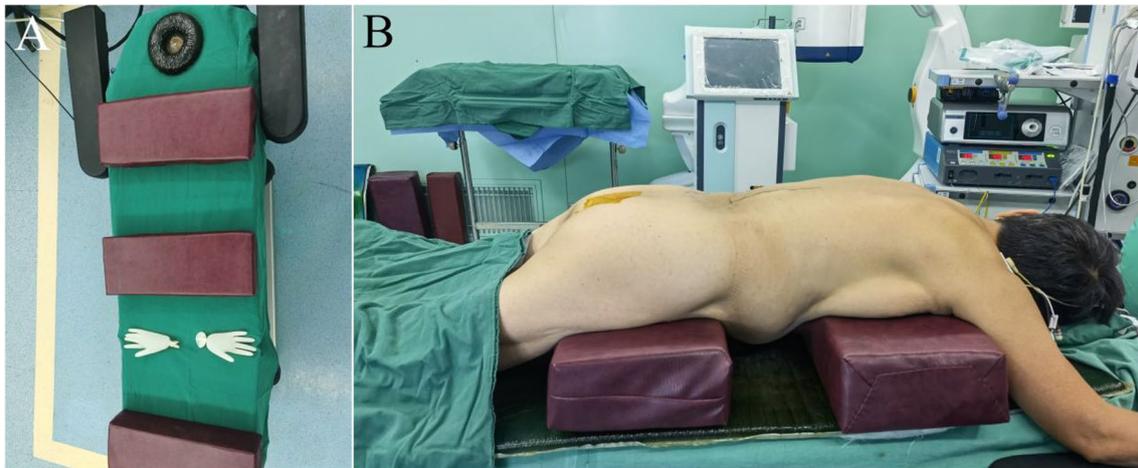
The purpose of the present study was to compare the difference and correlation between the RKAs in the supine/prone position and the preoperative standing position, and to determine whether preoperative MRI can be used for SK flexibility assessment in patients with kyphosis secondary to so-OTLF.

## Method

### Patient sample

The study group included 37 patients (8 males and 29 females) with kyphosis secondary to so-OTLF. All patients underwent posterior corrective fusion from December 2016 to May 2022. They also underwent preoperative standing X-rays, preoperative supine MRI, and intraoperative prone X-rays. Intraoperative prone RKA was measured using the thoracolumbar radiographs of the spinal frame that were obtained in the prone position after the induction of general anesthesia just before the beginning of the surgery. The surgical frame had one anterior chest pad and one pelvic pad. All patients were positioned on the frame with hips and knees in slight flexion (Fig. 1). The inclusive criteria are as follows: (1) patients who were diagnosed with kyphosis secondary to so-OTLF and have received posterior corrective fusion surgery, (2) fractured vertebrae at T11 to L2 location, (3) RKA measured on standing X-ray radiograph greater than 30°, (4) disease duration longer than 2 months, (5) bone mineral density: *T* score of  $\leq -2.5$ , and (6) complete imaging data. The exclusion criteria are as follows: (1) spinal tuberculosis, infection, and tumor; (2) incomplete imaging data; (3) the coronal Cobb angle  $> 10^\circ$ ; and (4) combined with other vertebral fractures and other types of kyphosis, such as degenerative kyphosis.

The Institute's Institutional Review Committee and Ethics Committee approved the study (Institutional Review Committee No. 2017-01).



**Fig. 1** **A** Surgical frame image viewed from the top of the table. **B** Intraoperative prone position. Patients were positioned on the frame with hips and knees in slight flexion. The spinal frame consisted of one anterior chest pad and one pelvic pad

### Imaging evaluation

RKA is the angle between the superior end plate of the proximal vertebral body and the inferior end plate of the distal vertebral body of the wedge-shaped vertebra. Thoracic kyphosis (TK) is the angle between the upper end plate of T5 and the lower end plate of T12. Lumbar lordosis (LL) is the angle between the upper end plate of L1 and the upper end plate of S1. Sagittal vertical axis (SVA) is the distance between the center of the C7 vertebral body on the full-length lateral film of the spine to the posterior upper border of S1. If the vertical line is in front of the rear upper edge of S1, then the value is positive; otherwise, the value is negative. A typical case is shown in Fig. 2.

## Result

### General information

Eight men and twenty-nine women met the inclusion criteria. The average age of patients was 66.3 years (53–81 years). The course of the disease was 2–36 months, with an average of 8.2 months. A unilateral vertebral fracture occurred in 25 patients (67.6%). Twelve cases (32.4%) had multiple vertebral fractures (as shown in Table 1).

The average SVA in the standing position before the operation was  $51.1 \pm 43.1$  mm ( $-6.2$  mm to  $19.3$  mm). The average RKA was  $48.0^\circ \pm 12.4^\circ$  ( $30.2^\circ$ – $88.8^\circ$ ). The average LL was  $30.1^\circ \pm 19.5^\circ$  ( $-5.9^\circ$  to  $75.3^\circ$ ). The average TK was  $38.2^\circ \pm 20.3^\circ$  ( $1.4^\circ$ – $79.6^\circ$ ). The imaging parameters of spinal alignment in the standing position are shown in Table 2.

### Changes in RKA by different positions

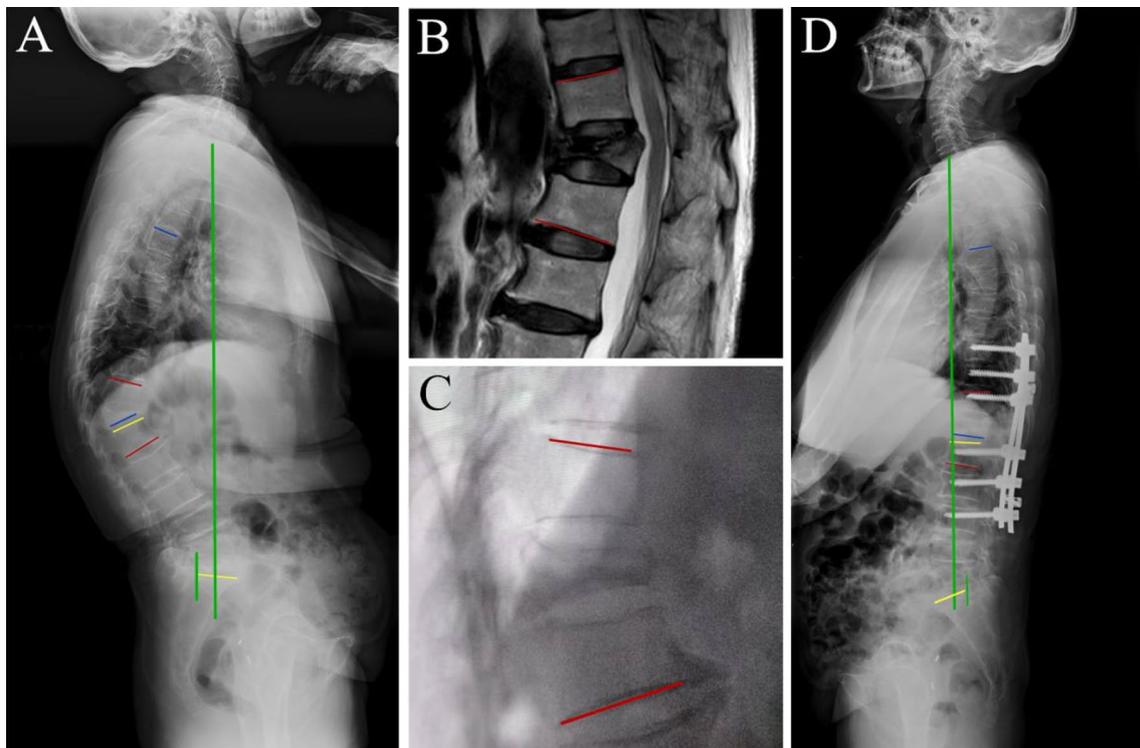
The RKAs measured on standing radiographs, supine MRI, and intraoperative prone radiographs were  $48.0^\circ$ ,  $34.4^\circ$ , and  $32.0^\circ$ , respectively (Fig. 3A). Compared with the RKA measured in standing position, the RKA measured on supine MRI decreased by  $13.6^\circ$  (95% confidence interval  $11.4^\circ$ – $15.8^\circ$ ), whereas that measured on intraoperative prone radiographs decreased by  $16.1^\circ$  (95% confidence interval  $13.7^\circ$ – $18.5^\circ$ ). A linear correlation existed between the SK flexibility measured on supine MRI and that measured on intraoperative prone radiographs, with an average difference of  $2.4^\circ$  ( $R^2 = 0.912$ ,  $p < 0.001$ ) (Fig. 3B). The mean RKA and SK flexibility are summarized in Table 3.

### Data analysis

SPSS 22.0 (IBM, Armonk, NY, USA) was applied to analyze all data. Continuous variables were expressed as mean  $\pm$  standard deviation. Counting data Chi-squared inspection was used. The measurement data were evaluated by *t*-test, and  $p < 0.05$  means the difference was statistically significant.

### Discussion

Spinal fractures commonly occur in the thoracolumbar segment because it is where the thoracic and lumbar vertebrae meet; this region is unprotected by the ribs and has remarkable mechanical stress and mobility [14]. Inappropriate treatment or even no treatment further aggravates kyphosis; thus, secondary kyphosis



**Fig. 2** Typical case: female, 68 years old, patient with kyphosis secondary to so-OTLF. She was treated with posterior single-segment Ponte osteotomy and fusion. **A** Image of preoperative standing radiograph; standing RKA: 47.5°, SVA: 26 mm. **B** Image of MRI in supine position; supine RKA: 27.8°. **C** Image of intraoperative radiograph; intraoperative RKA: 26.7°. **D** Image of postoperative standing radiograph; postoperative standing RKA: 8.1°, SVA: 20 mm

**Table 1** Demographics of all the 37 patients

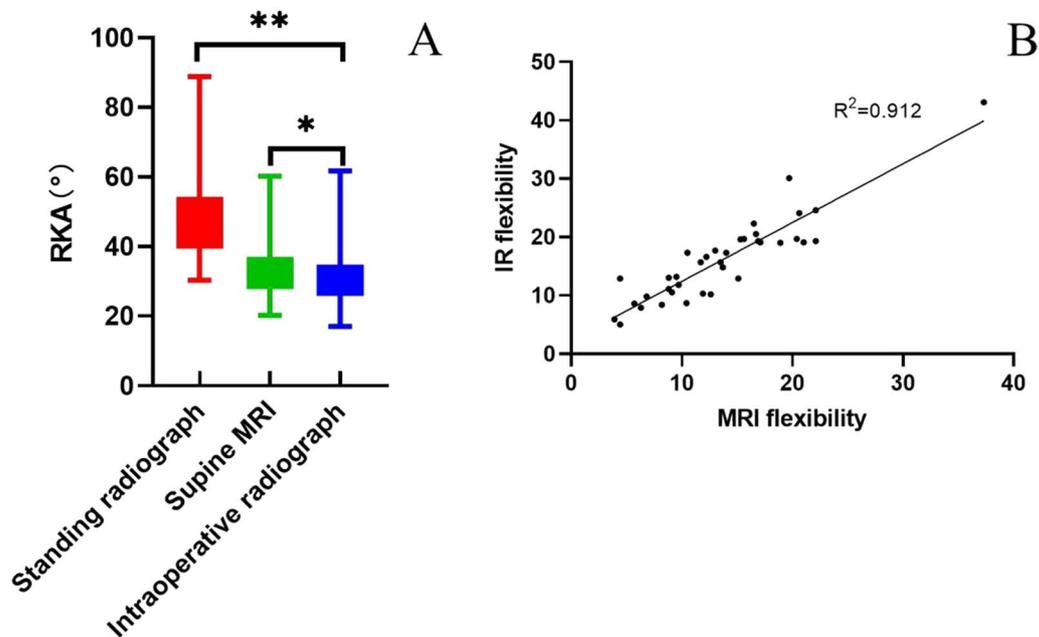
Characteristic	Value
Age (y)	66.3 ± 8.1
Gender	
Men (%)	8 (21.6%)
Women (%)	29 (78.4%)
Fracture location	
T11	2
T12	9
L1	10
L2	4
T12, L1	8
T12, L1, L2	4
Course of disease (month)	8.2 ± 6.7

deformity is formed, causing intractable low back pain, neurological dysfunction, and other complications in patients and posing a threat to the physical and mental health of middle-aged and elderly people [15–17]. Some studies [18, 19] found that when the RKA is greater than or equal to 30°, patients are at increased risk of

**Table 2** Spine sagittal radiographic parameters in standing position

Parameter	Preoperative standing radiographs
SVA (mm)	51.1 ± 43.1
RKA (°)	48.0 ± 12.4
LL (°)	30.1 ± 19.5
TK (°)	38.2 ± 20.3

chronic pain in the kyphosis area. Pain first occurs at the location of the deformity. Some patients may also complain of pain near the kyphosis area because localized kyphosis alters the normal biomechanics of the patient’s spine, causing premature degeneration of the vertebral levels above and below the deformity. Surgery is usually required when a patient presents with intractable low back pain, remarkable sagittal imbalance, or symptoms of spinal nerve compression. Therefore, a surgical osteotomy is usually performed in the apical region of kyphosis to correct the regional kyphosis of the thoracolumbar segment; thus, the sagittal balance



**Fig. 3** **A** RKAs measured on standing radiographs, supine MRI, and intraoperative prone radiographs were 48.0°, 34.4°, and 32.0°. Compared with the RKA measured in standing position, the RKA measured on supine MRI decreased by 13.6° (95% confidence interval 11.4°–15.8°), whereas the RKA measured on intraoperative prone radiographs decreased by 16.1° (95% confidence interval 13.7°–18.5°). **B** Graph showing the linear dependency between SK flexibility measured on magnetic resonance imaging (MRI) (horizontal axis) and on Intraoperative radiograph (IR) (vertical axis). IR flexibility is on average 2.4° higher than flexibility of sagittal kyphosis curve on MRI ( $R^2 = 0.912, p < 0.001$ )

**Table 3** Mean RKA and mean SK flexibility measured in different position

Position	Mean RKA	Mean SK flexibility(95% CI)
Standing (°)	48.0 ± 12.4	
Suspine MRI (°)	34.4 ± 10.6	13.6 (95% confidence interval 11.4–15.8)
Intraoperative prone (°)	32.0 ± 9.7	16.1 (95% confidence interval 13.7–18.5)

of patients can be obtained and maintained, and the neurological symptoms can be improved [20, 21].

The severity of kyphosis deformity and the presence or absence of sagittal imbalance in the standing position should be considered first when making a surgical plan. The flexibility of the kyphosis deformity must also be evaluated before surgery [1, 11, 15]. RKA, usually measured on a standing spinal lateral X-ray radiograph before surgery, is considered an important indicator of the severity of kyphosis deformity in the spine [22]. Patients are typically in a forward protective posture when standing because of the effects of gravity, persistent back pain, and nerve traction pain caused by spinal stenosis; some elderly patients with weak back muscles cannot even stand entirely, thereby leading to

an excessive measured RKA [11, 17]. This measured value does not reflect the actual intraoperative degree of regional kyphosis in patients with kyphosis secondary to so-OTLF, and its clinical application relevance is greatly reduced. Similarly, we found that preoperative standing RKA and intraoperative prone RKA after general anesthesia were not the same in clinical practice. Under general anesthesia, the RKA was reduced to a certain extent; sometimes, it exceeded 50%. Although obtaining full-length X-ray radiographs of a standing spine in the lateral position was straightforward, affordable, and quick, the compensating angle brought on by discomfort and the effects of gravity was not easy to eliminate.

Putto et al. [23] took lateral radiographs with padding at the apex of kyphosis, which can measure the passive reducibility of kyphosis and the extent of the remaining correction (sometimes up to 50%), which may change the entire surgical approach. However, this finding was not investigated in further detail because the authors emphasized only the judgment of intervertebral stability rather than the assessment of flexibility. The X-ray radiographs of lumbar spine flexion and extension positions are often used in clinical diagnosis and treatment of lumbar degenerative diseases to evaluate the stability of the interbody, suggesting that the change in the sagittal curvature of

the interbody is the embodiment of flexibility. However, the increase in the patient's back muscle activity and the aggravation of back pain during the dynamic overextension and overflexion position limit or prevent the activity of some patients; thus, using dynamic position radiographs to judge sagittal kyphosis flexibility becomes inaccurate [11]. When the patient is lying down during an MRI examination, the patient's back muscles can be completely relaxed, and the protective anteversion brought on by discomfort can also be reduced. Due to the short examination time, these factors cannot be completely eliminated in CT examination [24]. Kaiser et al. [12] found a linear dependency between hyperextension radiograph and MRI flexibility with a mean difference of  $9.3^\circ$  ( $R^2=0.61$ ,  $p<0.001$ ) by using the imaging data of 18 Scheuermann kyphosis patients. They demonstrated that preoperative MRI has a similar predictive value to bolster-assisted hyperextension lateral radiograph for the Scheuermann kyphosis flexibility assessment. Sharma A et al. analyzed the imaging data from 138 patients with sagittal imbalance. They found that a mean difference of  $2.9^\circ$  exists between the LL measured on supine MRI and that measured on intraoperative X-rays, as opposed to the  $5.53^\circ$  mean difference between standing X-rays and intraoperative X-rays [13]. In patients with flexible deformities ( $n=24$ ), the lumbar lordosis on MRI measured a discrepancy of  $3.08^\circ$ , as compared to a discrepancy of  $11.46^\circ$  when measured with standing X-ray. This finding showed that preoperative MRI effectively identifies flexible sagittal abnormalities. Moreover, it indicated that the LL recorded on MRI more correctly predicts the intraoperative LL than that measured on standing X-ray in cases of flexible sagittal abnormalities. Similarly, we hypothesized that the MRI examination in supine position could eliminate the factors of protective anteversion caused by intractable back pain, gravity, and nerve traction pain; thus, highly accurate RKA could be obtained.

We evaluated 37 patients (8 males and 29 females) with kyphosis secondary to so-OTLF, with an average age of 66.3 years. The RKAs measured on standing X-ray radiographs, supine MRI, and prone X-ray radiographs before the operation were  $48.0^\circ$ ,  $34.4^\circ$ , and  $32.0^\circ$ . Compared with the RKA measured in standing position, the RKA measured on supine MRI decreased by  $13.6^\circ$  (95% confidence interval  $11.4^\circ$ – $15.8^\circ$ ), whereas the RKA measured on intraoperative prone radiographs decreased by  $16.1^\circ$  (95% confidence interval  $13.7^\circ$ – $18.5^\circ$ ). In the present study, the RKA measured on intraoperative prone radiographs was significantly decreased compared with that measured on standing radiographs ( $p<0.001$ ). This finding suggests that postural reduction of the surgical frame during surgery significantly reduced the RKA measured on intraoperative prone radiographs. The SK flexibility measured on

supine MRI was significantly linearly related to the actual SK flexibility during operation, with an average difference of  $2.4^\circ$  ( $R^2=0.912$ ,  $p<0.001$ ). This finding indicates that supine MRI can be used to assess SK flexibility in patients with kyphosis secondary to so-OTLF. Moreover, the difference between the RKA measured with preoperative MRI and the actual RKA during the operation was only  $2.4^\circ$ .

Although supine MRI cannot perfectly reflect all the information of the prone position on the operating frame, as a non-weight-bearing imaging examination, it can convey the relevant information about SK flexibility. With a flexible deformity, a large portion of the correction was obtained by positioning only a surgical frame. Moreover, aggressive corrective maneuvers may not be necessary. We used supine MRI to assess the SK flexibility of patients with kyphosis secondary to so-OTLF to develop surgical protocols that can benefit individual patient management. Additionally, preoperative MRI, routinely performed in such patients to exclude neuroaxis pathologies or any compressive cord lesion before, does not increase the economic burden of the patient and the absorption of ionizing radiation.

Given the small sample size, the present study only makes some preliminary discussions on the differences between different positions. It cannot analyze the the apex of the deformity in groups. Thus, a large sample size is required. During the operation, we used the C-arm to perform fluoroscopy with the posterior convex apex as the center. Some images of multiple vertebral fractures need to be spliced, which may have some errors. Furthermore, although different spinal frames might affect RKA in the prone position, we only evaluated one type of frame, and validation using various frames will be required.

## Conclusion

The degree of regional kyphosis deformity was reduced by self-reduction of the intraoperative surgical frame. With a predictive value similar to an intraoperative prone radiograph, preoperative supine MRI can be used for SK flexibility assessment in patients with kyphosis secondary to so-OTLF. The ability to predict the intraoperative degree of regional kyphosis deformity with positioning before the operation helps with surgical planning and patient counseling regarding expectations and risks of surgery.

## Abbreviations

MRI	Magnetic resonance imaging
SK	Sagittal kyphotic
so-OTLF	Symptomatic old osteoporotic thoracolumbar fracture
RKA	Regional kyphosis angle
TK	Thoracic kyphosis

LL	Lumbar lordosis
SVA	Sagittal vertical axis
IR	Intraoperative radiograph
CI	Confidence interval

### Acknowledgements

There is no additional person who has contributed to this study except the authors.

### Author contributions

YH, CX, and WK contributed to the conception of the study; ZF, SL, YW, and WK are responsible for collecting data; WK and ZY contributed significantly to analysis and manuscript preparation; WK performed the data analyses and wrote the manuscript; and YH helped perform the analysis with constructive discussions. All authors reviewed the manuscript. All authors read and approved the final manuscript.

### Funding

This work was supported by Health Commission of Anhui province (No. AHWJ2021b111), Health Commission of Fuyang City (No. 2021-1), and Anhui Medical University Fund project (2021xkj210). Funding sources did not play a role in investigation.

### Availability of data and materials

The patients' data were collected in the Affiliated Fuyang People's Hospital of Anhui Medical University. The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

### Declarations

#### Ethics approval and consent to participate

The current study was approved by the ethical committee of Affiliated Fuyang People's Hospital of Anhui Medical University before data collection and analysis. Written informed consent to participate was obtained from all participants.

#### Competing interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

#### Author details

<sup>1</sup>Department of Orthopedics, Affiliated Fuyang People's Hospital of Anhui Medical University, 501 Sanqing Road, Fuyang 236000, Anhui, China. <sup>2</sup>Spinal Deformity Clinical Medicine and Research Center of Anhui Province, 501 Sanqing Road, Fuyang 236000, Anhui, China. <sup>3</sup>School of Mechatronics Engineering and Automation, Shanghai University, 333 Nanchen Road, Shanghai 200072, China.

Received: 20 January 2023 Accepted: 16 February 2023

Published online: 23 February 2023

### References

- Picazo DR, Villaescusa JR, Martínez EP, Pérez FD. Late collapse osteoporotic vertebral fracture in an elderly patient with neurological compromise. *Eur Spine J*. 2014;23(12):2696–702.
- Grevitt M, Kamath V, Avadhani A, et al. Correction of thoracic kyphosis with Ponte osteotomy. *Eur Spine J*. 2010;19(2):351–2.
- Hu X, Thapa AJ, Cai Z, et al. Comparison of smith-petersen osteotomy, pedicular subtraction osteotomy, and poly-segmental wedge osteotomy in treating rigid thoracolumbar kyphotic deformity in ankylosing spondylitis a systematic review and meta-analysis. *BMC Surg*. 2016;16:4.
- Lazennec JY, Neves N, Rousseau MA, Boyer P, Pascal-Mousselard H, Saillant G. Wedge osteotomy for treating post-traumatic kyphosis at thoracolumbar and lumbar levels. *J Spinal Disord Tech*. 2006;19(7):487–94.
- Xia L, Li P, Wang D, et al. Spinal osteotomy techniques in management of severe pediatric spinal deformity and analysis of postoperative complications. *Spine*. 2015;40:286–92.
- Nakashima H, Yukawa Y, Ito K, Machino M, Ishiguro N, Kato F. Combined posterior-anterior surgery for osteoporotic delayed vertebral fracture with neurologic deficit. *Nagoya J Med Sci*. 2014;76(3–4):307–14.
- Rajasekaran S, Rajoli SR, Aiyer SN, Kanna R, Shetty AP. A classification for kyphosis based on column deficiency, curve magnitude, and osteotomy requirement. *J Bone Joint Surg Am*. 2018;100(13):1147–56.
- Buchowski JM, Kuhns CA, Bridwell KH, Lenke LG. Surgical management of posttraumatic thoracolumbar kyphosis. *Spine J*. 2008;8:666–77.
- Schoenfeld AJ, Wood KB, Fisher CF, et al. Posttraumatic kyphosis: current state of diagnosis and treatment: results of a multinational survey of spine trauma surgeons. *J Spinal Disord Tech*. 2010;23(7):e1–8.
- Li X, Zhang J, Tang H, Lu Z, Chen S, Hong Y. Closing-opening wedge osteotomy for thoracolumbar traumatic kyphosis. *Eur J Med Res*. 2014;19(1):59.
- Mazel C, Ajavon L. Malunion of post-traumatic thoracolumbar fractures. *Orthop Traumatol Surg Res*. 2018;104(15):S55–62.
- Kaiser R, Behrbalk E, Walsh M, Waldauf P, Perez Romera AB, Mehdian H. Can MRI predict flexibility in Scheuermann kyphosis patients? *Clin Spine Surg*. 2017;30(7):E938–41.
- Sharma A, Pourtaheri S, Savage J, et al. The utility of preoperative magnetic resonance imaging for determining the flexibility of sagittal imbalance. *Neurosurgery*. 2018;83(3):465–70.
- Kato S, Murray JC, Kwon BK, Schroeder GD, Vaccaro AR, Fehlings MG. Does surgical intervention or timing of surgery have an effect on neurological recovery in the setting of a thoracolumbar burst fracture? *J Orthop Trauma*. 2017;31(Suppl 4):S38–43.
- Alpantaki K, Dohm M, Korovessis P, Hadjipavlou AG. Surgical options for osteoporotic vertebral compression fractures complicated with spinal deformity and neurologic deficit. *Injury*. 2018;49(2):261–71.
- Horton WC, Brown CW, Bridwell KH, Glassman SD, Suk SI, Cha CW. Is there an optimal patient stance for obtaining a lateral 36° radiograph? A critical comparison of three techniques. *Spine*. 2005;30(4):427–33.
- Prost S, Pesenti S, Fuentes S, Tropiano P, Blondel B. Treatment of osteoporotic vertebral fractures. *Orthop Traumatol Surg Res*. 2021;107(15):102779.
- Malcolm BW, Bradford DS, Winter RB, Chou SN. Post-traumatic kyphosis. A review of forty-eight surgically treated patients. *J Bone Joint Surg Am*. 1981;63(6):891–9.
- Gertzbein SD, Scoliosis Research Society. Multicenter spine fracture study. *Spine*. 1992;17(5):528–40.
- Ma Z, Jiao J, Yang D, Ding W. Posterior vertebral column resection combined with bone cement augmentation of pedicle screw fixation for treatment of severe vertebral compression fractures with kyphotic deformity: a retrospective case series. *Clin Spine Surg*. 2020;33(6):E269–75.
- Krishnakumar R, Lenke LG. "Sternum-into-abdomen" deformity with abdominal compression following osteoporotic vertebral compression fractures managed by 2-level vertebral column resection and reconstruction. *Spine*. 2015;40(18):E1035–9.
- Kuklo TR, Polly DW, Owens BD, Zeidman SM, Chang AS, Klemme WR. Measurement of thoracic and lumbar fracture kyphosis: evaluation of intraobserver, interobserver, and technique variability. *Spine*. 2001;26(1):61–6.
- Putto E, Tallroth K. Extension-flexion radiographs for motion studies of the lumbar spine. A comparison of two methods. *Spine*. 1990;15(2):107–10.
- Epstein O, Ludwig S, Gelb D, Poelstra K, O'Brien J. Comparison of computed tomography and plain radiography in assessing traumatic spinal deformity. *J Spinal Disord Tech*. 2009;22(3):197–201.

### Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.