



# Dynamic magnetic resonance imaging parameters for objective assessment of the magnitude of tethered cord syndrome in patients with spinal dysraphism

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Received: 6 February 2018 / Accepted: 27 October 2018 / Published online: 20 November 2018  
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## Abstract

**Background** Dynamic magnetic resonance imaging (MRI)-based criteria for diagnosing magnitude of tethered cord syndrome (TCS) in occult spinal dysraphism are proposed.

**Methods** In this prospective, case-control design study, MRI lumbosacral spine was performed in 51 subjects [*pilot group* ( $n = 10$ ) without TCS (for defining radiological parameters), *control group* ( $n = 10$ ) without TCS (for baseline assessment), and *study group* ( $n = 31$ ) with spinal dysraphism (thick filum terminale [ $n = 12$ ], lumbar/lumbosacral meningocele [ $n = 6$ ], and lipomyelomeningocele [ $n = 13$ ]). The parameters compared in control and study groups included *oscillatory frequency* (OF), difference in ratio, in supine/prone position, of distance between posterior margin of vertebral body and anterior margin of spinal cord (*oscillatory distance* [OD]), with canal diameter, at the level of conus as well as superior border of contiguous two vertebrae above that level; *delta bending angle* ( $\Delta BA$ ), difference, in supine/prone position, of angle between longitudinal axis of conus and that of lower spinal cord; and *sagittal and axial root angles*, subtended between exiting ventral nerve roots and longitudinal axis of cord. An outcome assessment at follow-up was also done.

**Results** In the study group (cord tethered), significantly less movement at the level of conus (OF0,  $p = 0.013$ ) and one level above (OF1,  $p = 0.03$ ) and significant difference in  $\Delta BA$  ( $p = 0.0$ ) were observed in supine and prone positions, compared to controls. Ventral nerve root stretching resulted in sagittal/axial root angle changes. Median OF (0.04) in the lipomyelomeningocele group was significantly less than that in control group (0.23). Median OF was also lesser in patients with thick filum terminale or meningocele. Difference in median sagittal and axial root angles among the study and control groups was statistically significant ( $p = 0.00$ ).

**Conclusion** New dynamic MRI-based parameters to establish the presence and magnitude of TCS have been defined. OF measured the extent of loss of translational cord displacement in supine and prone positions;  $\Delta BA$  defined the relative angulation of conus with lower spinal cord, and sagittal and axial root angles represented ventral nerve root stretching. The difference in OF or  $\Delta BA$  was minimum in the group with thick filum terminale and progressively increased in the groups with lipomyelomeningocele and meningocele.

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This article is part of the Topical Collection on *Spine - Other*

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**Keywords** Spinal dysraphism · Tethered cord syndrome · Magnetic resonance imaging · Thick filum terminale · Meningomyelocele · Lipomyelomeningocele

## Introduction

Spinal dysraphic states may lead to the clinical manifestations of tethered cord syndrome including neurological deficits, back pain, sphincteric dysfunction, and orthopedic abnormalities such as congenital talipes equinovarus, limb shortening, and scoliosis [6, 19]. Although the presence of tethered cord syndrome (TCS) may be detectable based on the conventionally described anatomical parameters such as a low-lying cord or the associated presence of occult or overt spinal dysraphism, dynamic parameters based on supine and prone positions of the patients that conclusively indicate the presence of this condition have not been established. Even when a dysraphic state exists in a patient, information on whether or not its presence will later on lead to neurological deficits due to coexistent cord stretching is still nebulous. Following surgery for detethering, symptomatic re tethering may occur in 7–9% of patients who have undergone sectioning of a thick filum terminale, and in nearly 35% patients in whom meningomyelocele or lipomyelomeningocele repair has been performed [21]. In this situation, the anatomical criteria that define the presence of a dysraphic entity or that of a low-lying conus are no longer relevant in establishing the diagnosis of re tethering of the spinal cord. This study aims to establish novel magnetic resonance (MR)-based dynamic criteria based on evaluation for evidence of TCS in both supine and prone positions of the patient and to correlate them with the neurological outcome.

## Material and methods

The article is written according to the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) Statement guidelines. Individual consent from the patient to use clinical and radiological details for publication was taken. Institutional ethical clearance (IEC 2017-95-MCh-EXP) was obtained, and there was no conflict of interest.

### Patient spectrum

In this prospective case-control design study, conducted from January 1, 2016 to December 31, 2017, a magnetic resonance imaging (MRI) of the lumbosacral spine was performed in 51 subjects. This included a *pilot group* consisting of 10 patients with either cervical spondylosis ( $n = 6$ ) or an intradural, extramedullary lesion ( $n = 4$ ) without any evidence of cord tethering, in whom an MRI was done in supine position only

to define the radiological parameters (oscillatory distance and bending angle) used in the study. This group did not form a part of the study analysis. The *control group* consisted of 10 patients without cord tethering (who were undergoing an MRI for either a posterior fossa tumor [ $n = 6$ ] or congenital hydrocephalus [ $n = 4$ ]). In this group, a craniospinal MRI was undertaken, and our predefined parameters, in supine and prone positions of the patient, were noted. The radiological parameters obtained from this group of patients formed the baseline parameters for comparison with the study group. The *study group* consisted of 31 patients of spinal dysraphism with tethered cord (12 patients with a thick filum terminale, 6 patients with lumbar/lumbosacral meningomyelocele, and 13 patients with lipomyelomeningocele), in whom a lumbosacral MRI was done in supine and prone positions. A 3-T MRI (General Electric; Boston, MA 02210) machine was used. The patients underwent a MRI, including sagittal T1 and T2 and axial T1 and T2-weighted (W) sequences of the lumbar spine in the supine position, with sagittal and axial T2W sequences also being repeated in the prone position. Two radiologists independently measured the study parameters using the same MRI software, digital imaging and communications in medicine-advantage workstation (DICOM-ADW). General anesthesia was not required by any patient in the group.

### Study parameters

Tethered cord was considered when one of the three radiological entities existed in the patients: a thick and short filum terminale, a meningomyelocele, or a lipomyelomeningocele. This was either associated with a low-lying conus below the lower border of L3 vertebra ( $n = 17$ , 54.8%) or the conus at the normal level ( $n = 14$ , 45.2%). In case a patient had the simultaneous association of a thick filum terminale with either a meningomyelocele ( $n = 5$ ) or a lipomyelomeningocele ( $n = 3$ ), then he/she was considered in the category of meningomyelocele or lipomyelomeningocele, respectively. There was no patient in the series with purely a thick and short filum terminale with the conus at the normal level. Among patients with a meningomyelocele ( $n = 6$ ), the conus was in its normal position in 5 patients and low-lying in 1 patient, whereas among patients with a lipomyelomeningocele, the conus was in its normal position in 3 patients and low-lying in 10 patients (Table 1).

Table 2 defines the radiological parameters used in the study. In the pilot group, the methodology for measuring the new radiological parameters (oscillatory distance and bending angle) to define tethering was identified in supine position of the subject.

**Table 1** Clinical features and associated anomalies among 31 patients of the study group with tethered cord syndrome

Patient spectrum	Number
Clinical signs and symptoms	8 (25.8%)
• Asymptomatic swelling	
• Difficulty in walking	15 (48.4%)
○ Unilateral or bilateral limb weakness	9 (29.03%)
○ Orthopedic deformities	2 (6.5%)
○ Limb shortening	4 (12.9%)
• Sphincteric involvement (retention with overflow)	5 (16.12%)
• Sphincteric involvement (incontinence with loss of bladder sensation)	4 (12.9%)
Associated anomalies	
Split cord malformation	3 (9.7%)
Hydrocephalus	2 (6.5%)
Chiari malformation type I	2 (6.5%)
Tethered cord syndrome	
Thick filum terminale with low-lying cord	12 (38.7%)
Meningomyelocele	06 (19.4%) [5 had conus at normal level, 1 had a low-lying cord]
Lipomyelomeningocele	13 (41.9%) [3 had conus at normal level, 10 had a low-lying cord]
Level of conus	
Cord above L3	14 (45.2%)
Cord below L4	17 (54.8%)
Postoperative course	
Improvement	12 (38.7%)
Deterioration	5 (16.1%)
Same	14 (45.2%)
Postoperative complications	
Motor deterioration	2 (6.5%)
Bladder involvement	1 (3.2%)
Wound-related complications	4 (12.9%)

L lumbar

Following this, the lumbosacral sagittal (for assessment of the *oscillatory distance*, *oscillatory frequency*, *bending angle*, *delta bending angle*, and *sagittal root angle*) and axial (for assessment of *axial root angle*) T2W MRI imaging in the control as well as study groups was done in both supine and prone positions of the subject. The parameters were measured based on the following rationale:

#### A. Oscillatory distance and oscillatory frequency:

The forward movement of lower end of the cord with change in position from supine to prone is likely to be of a greater magnitude in a normal individual than in a patient with

tethered cord syndrome. In the latter group of patients, the traction on the cord as a result of tethering inhibits this natural translational movement with respect to the supine and prone positions of the patient [21].

Oscillatory distance (OD) was defined as the ratio of the distance between the posterior margin of the vertebral body and the anterior margin of the spinal cord, with the canal diameter at the same level, taken at the level of the conus as well as the superior border of the contiguous two vertebrae above that level. This ratio at the level of the tip of conus was labeled as OD0, and the measured ratios at the superior border of the contiguous two vertebrae above that level, respectively, were labeled as OD1 and OD2. The OD at all these contiguous levels was measured in both supine and prone positions (Fig. 1a, b).

Oscillatory frequency (OF) was defined as the difference in OD in supine and prone positions at the three levels: the index level, i.e., OD0, and the superior borders of the contiguous two vertebrae above the index level, i.e., OD 1 and OD2. An OF less than 10% signified more traction on the cord in patients with TCS. An OF more than 10% signified a lax cord (that is usually associated in a cord without tethering).

#### B. Bending angle and delta bending angle:

Bending angle (BA) was defined as the acute angle (measured along the posterior aspect of the two axes) subtended by the longitudinal axis of the conus with the mid-sagittal plumb line drawn along the longitudinal axis of the lower spinal cord. In the control subjects, this angle was nearly 0°; in patients with a tethered cord (the study group), however, the longitudinal axis of the conus formed a posterior angulation with the mid-sagittal plumb line drawn along the longitudinal axis of the lower spinal cord, and therefore, an angle is subtended. This angle was measured on magnetic resonance (MR) images undertaken both in the supine and prone positions of the patient (Fig. 1c).

Delta ( $\Delta$ ) bending angle was defined as the change in the BA with the change in the patient's position from supine to prone. The cases with tethered cord syndrome were divided into three groups: those with  $\Delta$ BA less than 1 (either no or less tethering), between 1 and 10 (moderate tethering), and more than 10 (maximum tethering).

#### C. Sagittal root angle and axial root angle:

The relaxed ventral nerve roots in a normal individual follow a lax course in the horizontal plane creating an “inverted U” appearance. In a patient with tethered cord, bilateral ventral nerve roots are stretched creating a “V” shape on the T2W axial MR images, as they exit through their respective intervertebral foramina.

Sagittal root angle was defined, on the lumbosacral *sagittal* T2W MRI imaging in the control as well as study groups, as

**Table 2** Definitions used in the study for defining magnetic resonance imaging (MRI) parameters evaluating for tethered cord syndrome

Tethered cord syndrome (TCS)	TCS was considered when one of the three radiological entities existed in the patients, a thick and short filum terminale, a meningocele, or a lipomyelomeningocele <sup>a</sup>
Oscillatory distance (OD)	The ratio of the distance between the posterior margin of vertebral body and the anterior margin of spinal cord with the canal diameter at the same level, taken at the level of conus as well as superior border of the contiguous two vertebrae above the level of conus
Oscillatory frequency (OF)	The difference in oscillatory distance in supine and prone position
Bending angle (BA)	The acute angle subtended by the vertical axis of the conus with the midsagittal plumb line drawn along the vertical axis of the lower spinal cord
Delta bending angle ( $\Delta$ BA)	The change in bending angle was measured with change in position of the body from supine to prone.
Sagittal root angle	The superior angle between a line drawn along the exiting nerve root and the vertical plumb line in midsagittal plane of the cord
Axial root angle	The angle between a line drawn along the longitudinal axis of the exiting nerve root and vertical line bisecting the cord in axial plane at the level of tip of conus

<sup>a</sup> If a meningocele or lipomyelomeningocele coexisted with a short filum terminale, then the entity was considered in either of the former two categories (based on whether a meningocele or lipomyelomeningocele, respectively, coexisted)

the angle between a line drawn along the exiting nerve root and the vertical plumb line in the mid-sagittal plane of the cord (Fig. 2).

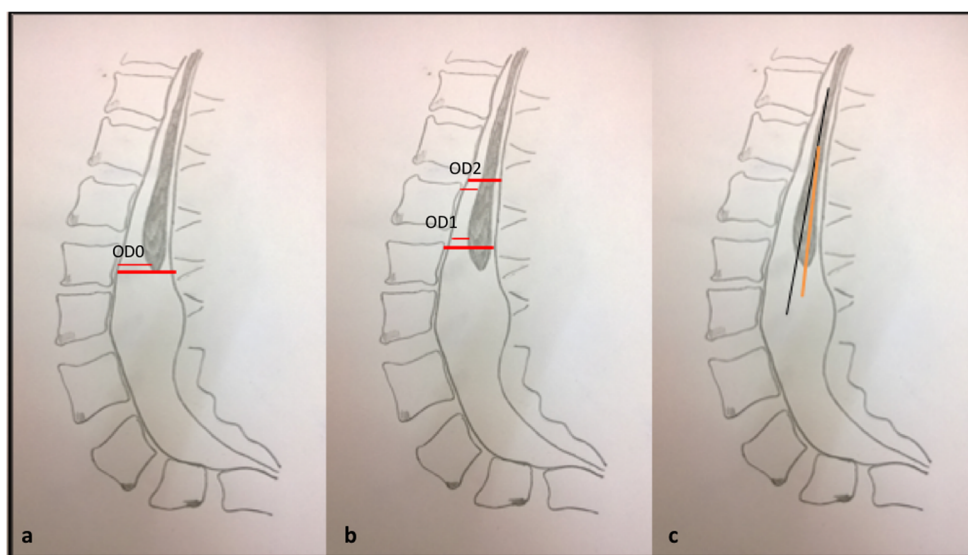
Axial root angle was defined, on the lumbosacral *axial* T2W MRI imaging in the control as well as study groups, done in both supine and prone positions of the subject, as the angle between a line drawn along the longitudinal axis of the exiting ventral nerve root in the horizontal plane and the vertical line bisecting the cord at the level of the conus (Fig. 3).

The above parameters were measured in the three different subgroups of patients with tethered cord syndrome, namely, a thick filum terminale with a low-lying cord, lipomyelomeningocele, and meningocele. The

differences of the parameters in these subgroups were noted and also compared with the control group.

### Exclusion parameters

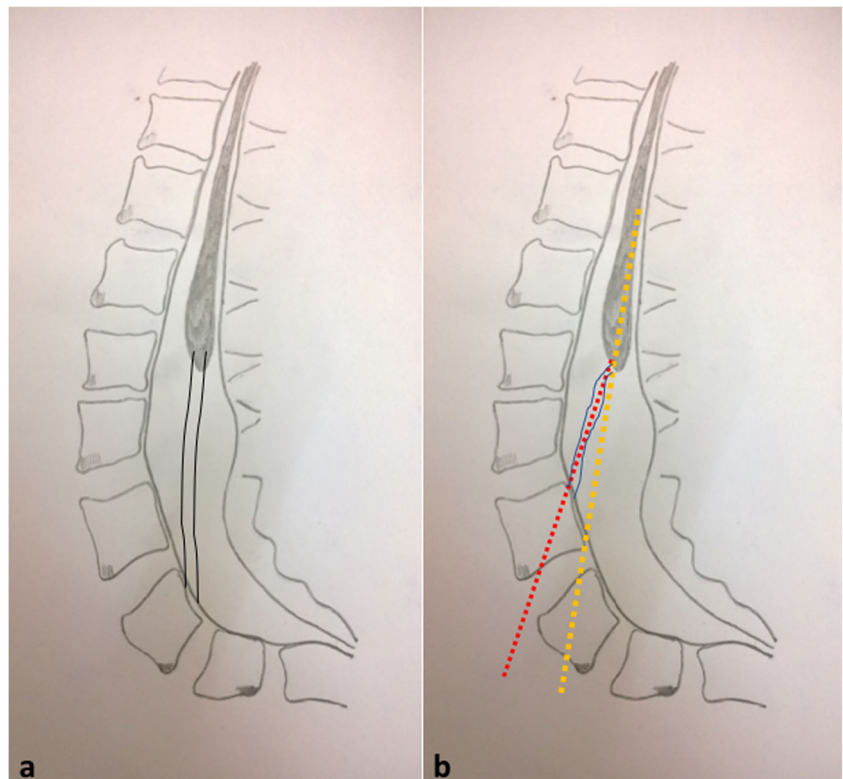
Patients who had already undergone a preoperative MRI prior to their admission to our institution, those with flaccid paraplegia with sphincteric involvement, those who were having an active cerebrospinal fluid leak from their posterior meningocele sac at the time of admission, and those with coexisting two-level cervical/upper thoracic cord tethering along with lumbar level tethering were excluded from the study.



**Fig. 1** Schematic representation of the MRI parameters (oscillatory distance [OD] and bending angle [BA]) proposed for assessing the presence and magnitude of tethered cord syndrome. **a** OD0: the distance from the posterior margin of the vertebral body at the level of tip of conus. The canal diameter at same level is also measured. **b**

OD1 and OD2: The distance from the posterior margin of the vertebral body at the level of upper margins of the contiguous two vertebrae above is also measured. The canal diameter at same levels is also assessed. **c** BA: angle subtended by the longitudinal axis of the lower cord (black line) with the longitudinal axis of conus (orange line)

**Fig. 2** **a** Schematic representation of sagittal image of the spine to demonstrate the sagittal nerve root angle. **a** Normal cord: The longitudinal axis of the lower cord is almost in line with the ventral nerve roots (black wavy lines) emerging from the level of the conus. **b** Tethered cord: The longitudinal axis (red arrow) of the emerging ventral roots is at an angulation with the longitudinal axis of the lower cord (orange arrow)



### Radiological outcome assessment

The radiological assessment was done at the time of discharge as well as the final follow-up of the patients ranging from 1 to 21 months (mean follow-up 9.48  $\pm$  standard deviation [SD] 6.9 months).

### Statistical analysis

The Statistical Package for the Social Sciences (SPSS) version 22.00 (IBM, New York) was used for statistical analysis. The confounding effect of age and gender distribution was compared using Fisher exact test and logistic regression, respectively. Independent Mann-Whitney *U* test was used to compare the

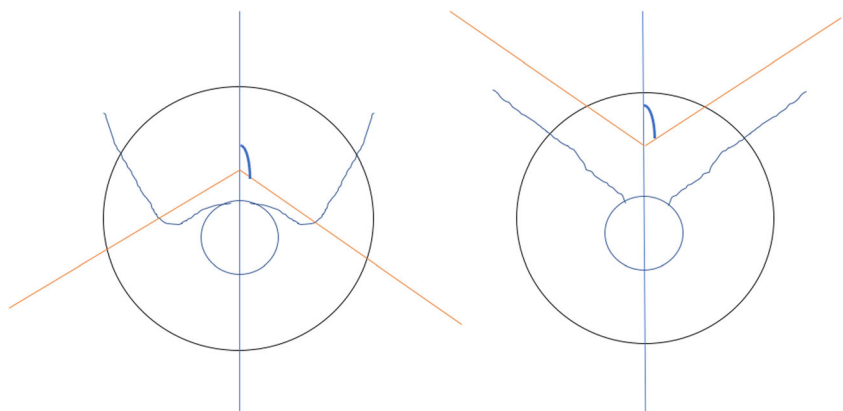
median distribution of study parameters among the cases and controls. Kruskal-Wallis test was used to compare the median distribution of study parameters among different subgroups. A *p* value of less than 0.05 was considered as significant.

## Results

### Patient spectrum

Among the 31 patients in the study group (21 [67.7%] male patients, median age 14 months, with 3 patients of age more than 10 years [aged 10, 12, and 21 years]) and the 10 subjects in the control group (6 [60%] male patients, median age

**Fig. 3** Schematic representation of the axial section of the spinal canal showing **a** in a normal individual, the lax ventral nerve roots form a “U”-shaped course prior to emerging from the intervertebral foramen; and, **b** in the presence of tethered cord, the axial sections show the stretched bilateral ventral nerve roots forming a “V”-shaped course



78 months, with 2 patients more than 10 years [aged 20 years and 25 years]), the age and gender distribution were comparable with no confounding effects on the outcome analysis ( $p = 0.35$  using Fischer exact test) (Table 3).

Table 1 summarizes the clinical spectrum in the study group consisting of patients with spinal dysraphism. The main presentations were a lumbar/lumbosacral swelling ( $n = 8$ , 25.8%), difficulty in walking ( $n = 15$ , 48.8%) due to unilateral or bilateral distal limb weakness ( $n = 9$ , 29.03%), orthopedic deformities like talipes equinovarus ( $n = 2$ , 6.5%) or limb shortening ( $n = 4$ , 12.9%), or sphincteric involvement ( $n = 9$ , 29%) in the form of retention with overflow ( $n = 5$ , 16.12%), or incontinence with loss of urinary bladder sensations ( $n = 4$ , 12.9%).

The patients in the series also had associated anomalies like spilt cord malformation ( $n = 3$ , 9.7%), hydrocephalus ( $n = 2$ , 6.5%), and Chiari I malformation ( $n = 2$ , 6.5%).

### Radiological parameters defined in the initial pilot study

Among the 10 patients in whom the baseline study parameters were defined on an MRI only in supine position of the patient, the median OD0 was  $0.63 \pm$  interquartile range (IQR) 0.3, the median OD1 was  $0.35 \pm 0.15$ , and the median OD2 was  $0.27 \pm 0.20$ . The median BA in this group in supine position only was  $0.00 \pm 0.95$  (range 0–12.2) degrees. These numerical values were only used to define the baseline parameters and not used for comparison with the values of the study group.

### Comparison between the study and the control group

The 10 patients in the control group included those whose MRI parameters in the supine and prone positions were measured (Table 4). The differences between OD0, OD1, and OD2 in supine and prone positions of the normal subjects were found to be statistically significant with the  $p$  values being 0.00 for all three levels. This demonstrated a significant change in position of the lower part of the spinal cord when there is a change in the normal subjects' position from supine to prone. The median  $\Delta$ BA was  $0.05 \pm$  IQR 1.00 (range 0.00–

3.00) degrees. The median distribution in study group and comparison is shown in Table 4 (Fig. 4).

A comparison of the radiological parameters was done using Mann-Whitney test (Table 4). The median distributions of OD, OF, and  $\Delta$ BA were compared between the control group and the study group. The median value of OD0 in supine position was higher than the values of OD1 and OD2 in the study and the control group due to the normal lordotic curvature of the lower cord and conus relative to the spine at that level. The comparison of median value of OD0 in supine position in the study and control groups was not significant ( $p = 0.21$ ).

The comparison of median value of OD0 in prone position in the study and control groups was, however, statistically significant ( $p = 0.00$ ). The OD1 and OD2 values in both supine and prone positions were also found to be significantly more in the patients in the study group when compared to the subjects in the control group.

The findings (Table 4) suggest that in the patients belonging to the study group, the difference in translational movements of the cord in supine and prone positions (OF) is significantly less when compared to the control group. At a higher level (OF2), the cord is relatively fixed by the denticulate ligaments or by the exiting nerve roots through the intervertebral foramina, so this movement at that level is less appreciable in normal subjects also ( $p = 0.135$ ).

The  $\Delta$ BA was also statistically significant when compared between the study and control groups ( $p = 0.0$ ) (Fig. 5).

Among the 31 patients in the study group, the sagittal and axial nerve root angles could be measured on MRI in 22 patients. In nine patients, the roots were not properly visible. The median sagittal root angle was  $172.65 \pm$  IQR 6.58 (range 155.10–178.00) degrees, the median left axial root angle was  $43.05 \pm 15.75$  (range 12.3–121.40) degrees, and median right axial root angle was  $43.7 \pm 21.93$  (range 18.0–134.0) degrees. Among the control group, all 10 root angles on both the sides could be measured. The median sagittal root angle was  $180^\circ$ . The median left axial root angle was  $111.35 \pm 25.75$  (range 67.7–121.0) degrees, and median right axial root angle was  $113.05 \pm 50.05$  (range 69.4–141.8) degrees. We found that bilateral ventrally exiting nerve roots were making an acute angle

**Table 3** Age and gender have no confounding effect on outcome when case and control groups were compared

Parameters	Study group	Control group	
Total number of cases	31	10	
Age	Median = 14 months $\pm$ IQR 100 (range 1–252)	Median = 78.00 months $\pm$ IQR 234 (range 5–300)	$p = 0.353$
Gender	Males = 67.7%	Males = 60.0%	$p = 0.654$

The distribution of age among cases and controls had no confounding effect on results. The median of both groups were compared using Fischer exact  $t$  test and Mann-Whitney test. Similarly, the gender among cases and controls had no confounding effect. The median distribution was compared using logistic regression analysis and it was found that in case group, 67.7% were males and in control group, 60% were males. IQR interquartile range

**Table 4** Comparing median distribution of study parameters among the study and the control groups

Parameters	Control	Cases	Significance based on independent Mann-Whitney <i>U</i> test
1. OD0 in supine position	Median = 0.47 ± IQR 0.19 (range = 0.25–0.69)	Median = 0.58 ± IQR 0.33 (range = 0.06–0.89)	<i>p</i> = 0.21
2. OD0 in prone position	Median = 0.22 ± IQR 0.08 (range = 0.15–0.47)	Median = 0.53 ± IQR 0.36 (range = 0.05–0.83)	<i>p</i> = 0.000
3. OD1 in supine position	Median = 0.34 ± IQR 0.10 (range = 0.22–0.40)	Median = 0.43 ± IQR 0.29 (range = 0.08–0.77)	<i>p</i> = 0.049
4. OD1 in prone position	Median = 0.18 ± IQR 0.02 (range = 0.14–0.22)	Median = 0.49 ± IQR 0.27 (range = 0.10–1.13)	<i>p</i> = 0.00
5. OD2 in supine position	Median = 0.26 ± IQR 0.07 (range = 0.17–0.37)	Median = 0.39 ± IQR 0.22 (range = 0.11–0.61)	<i>p</i> = 0.024
6. OD2 in prone position	Median = 0.18 ± IQR 0.04 (range = 0.15–0.23)	Median = 0.39 ± IQR 0.16 (range = 0.12–0.70)	<i>p</i> = 0.000
7. OF0	Median = 0.23 ± IQR 0.17 (range = 0.05–0.28)	Median = 0.09 ± IQR 0.13 (range = 0.00–0.69)	<i>p</i> = 0.013
8. OF1	Median = 0.16 ± IQR 0.12 (range = 0.06–0.22)	Median = 0.08 ± IQR 0.09 (range = 0.00–0.43)	<i>p</i> = 0.031
9. OF2	Median = 0.07 ± IQR 0.06 (range = 0.01–0.14)	Median = 0.04 ± IQR 0.08 (range = 0.00–0.29)	<i>p</i> = 0.135
10. ΔBA	Median = 0.05 ± IQR 1.00 (range = 0.00–3.00)	Median = 7.65 ± IQR 6.0 (range = 0.00–35.00)	<i>p</i> = 0.00

Values in italics were found to be significant

OD oscillatory distance, OF oscillatory frequency, ΔBA change in bending angle in supine and prone position, IQR interquartile range

(V shape) in patients of tethered cord syndrome as compared to the inverted U-shaped angle in the control group. The difference in the median sagittal and axial root angles among the study and control groups was statistically significant (*p* = 0.00). This formation of an acute angulation at the level of conus in the study group implies that the nerve roots are in a state of traction in patients with TCS.

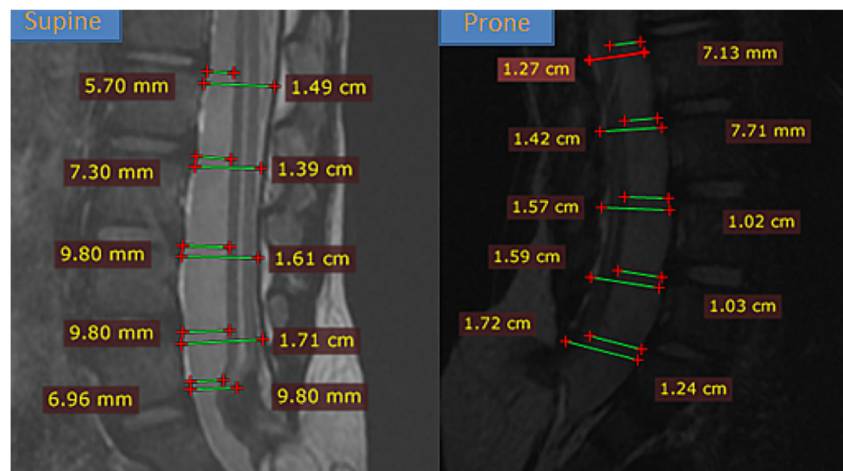
### Comparison between the subgroups

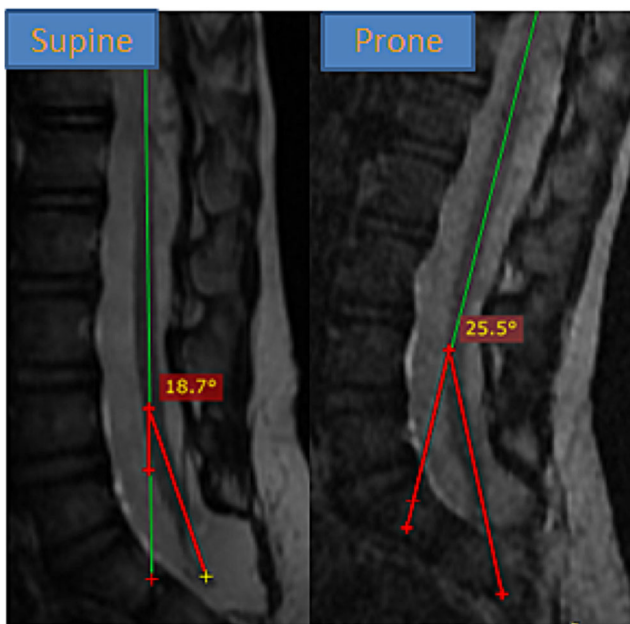
Details of median and interquartile range of the radiological parameters (OF and delta bending angle) in each subgroup are shown in Table 5.

The Kruskal-Wallis independent sample *t* test was used to compare the median distribution of OF0 among the groups, and the median OF0 in the lipomyelomeningocele group (0.04) was significantly lesser when compared to that in the control group (0.23). The median values of OF0 were also lesser in patients with a thick filum terminale and meningomyelocele subgroups, though not reaching statistical significance. The result implies that translational movement of conus decreases with increase in severity of tethering.

Similarly, on comparing the ΔBA, the *p* value was found to be statistically significant for all the subgroups when compared with the control group. This implies that

**Fig. 4** Oscillatory frequency assessed on sagittal T2W MRI in a patient with tethered cord syndrome by calculating the oscillatory distance between the supine and prone positions





**Fig. 5** Difference in bending angle (called delta bending angle) assessed on sagittal T2W MRI in a patient with tethered cord syndrome in supine and prone positions

with cord tethering, there is significant angulation of the conus compared with the longitudinal axis of the lower cord in all the three subgroups when compared with the control group.

### Immediate clinical outcome analysis using our radiological parameters

Table 6 focuses on analysis of the clinical outcome at follow-up with the preoperative oscillatory frequency and delta bending angle. There was no statistical significance between the radiological extent of tethering found in the study group in our patients and the clinical outcome at follow-up (Figs. 6a, b and 7a, b). Figure 6 shows postoperative improvement in OF.

**Table 5** Subgroup analysis of study patients with radiological parameters

Radiological parameters	Control group	Thick filum terminale	Meningomyelocele	Lipomyelomeningocele
OF0	Median = 0.23 ± IQR 0.17 (range = 0.05–0.28)	Median = 0.12 ± IQR 0.16 (range = 0.00–0.69) <i>p</i> = 0.09	Median = 0.03 ± IQR 0.28 (range = 0.02–0.36) <i>p</i> = 0.253	Median = 0.04 ± IQR 0.11 (range = 0.01–0.37) <i>p</i> = 0.005
OF1	Median = 0.16 ± IQR 0.12 (range = 0.06–0.22)	Median = 0.07 ± IQR 0.10 (range = 0.01–0.17) <i>p</i> = 0.053	Median = 0.15 ± IQR 0.27 (range = 0.01–0.43) <i>p</i> = 0.81	Median = 0.06 ± IQR 0.09 (range = 0.00–0.31) <i>p</i> = 0.014
OF2	Median = 0.07 ± IQR 0.06 (range = 0.01–0.14)	Median = 0.25 ± IQR 0.07 (range = 0.00–0.13) <i>p</i> = 0.41*	Median = 0.03 ± IQR 0.19 (range = 0.00–0.29) <i>p</i> = 0.41*	Median = 0.05 ± IQR 0.10 (range = 0.01–0.22) <i>p</i> = 0.41*
ΔBA	Median = 0.05 ± IQR 1.00 (range = 0.00–3.00)	Median = 8.05 ± IQR 7.00 (range = 3.0–30.00) <i>p</i> = 0.00	Median = 10.00 ± IQR 26.00 (range = 1.0–35.0) <i>p</i> = 0.003	Median = 7.00 ± IQR 6.00 (range = 0.0–12.0) <i>p</i> = 0.018

Kruskal-Wallis independent sample *t* test was used to compare median distribution among the groups. Values in italics were found to be significant  
OD oscillatory distance, OF oscillatory frequency, ΔBA change in bending angle in supine and prone position, IQR interquartile range

\*The distribution of OF2 is the same across the subgroups with a *p* value of 0.41

## Discussion

A dire need has been felt to propose dynamic radiological parameters that may unequivocally determine the presence of a TCS. There are several reasons for this requirement. First, the existing protocols to diagnose the anatomical entities responsible for TCS often do not have a correlation with the existing symptom complex of TCS. Second, there are several combinations of anomalies that come under the category of either occult or overt spinal dysraphism whose individual or simultaneous presence may contribute to the symptom complex of TCS. These include a thick filum terminale with a normal or low-lying spinal cord, an occult or overt spinal dysraphism with a normal or low-lying spinal cord [11], the simultaneous presence of an occult or overt spinal dysraphism with a thick filum terminale, and finally the simultaneous presence of an occult and overt spinal dysraphism with a normal or low-lying spinal cord [1]. All of them may or may not be associated with the clinical manifestations of TCS. Third, following the surgical procedure for detethering of the cord, the cord may or may not ascend up, and this phenomenon has no correlation with the relief in the clinical symptomatology obtained. Fourth, in patients with persistent or additional complaints at follow-up, there is no irrefutable parameter to determine whether or not spinal cord retethering has actually taken place, and that this phenomenon may have been responsible for the persistence or worsening of the neurological status of the patients.

The persistent stretching of distal spinal cord by inelastic tissue leading to functional loss and neurological deterioration is termed as tethered cord syndrome [7]. Several mechanisms have been proposed to explain the clinical manifestations of TCS in patients with a tethered cord [5, 9, 18, 26].

Several parameters have been proposed in the literature to help in diagnosing the presence of TCS. These include both static and dynamic parameters. Yamada and Lonser gave MRI



**Table 6** Comparison, using Kruskal-Wallis test, of the mean distribution of the oscillatory frequency at the index level, and the delta bending angle, with group of patients who improved, deteriorated, or remained the same at the follow-up visit

		Number of patients in subgroups	Urinary involvement	Difficulty in walking	Follow-up		
					Improvement	Deterioration	Same
Oscillatory frequency <i>p</i> = 0.707	< 0.1	16 (51.6%)	5/16	4/16	4 (25%)	2 (12.5%)	10 (62.5%)
	> 0.1	15 (48.4%)	4/15	11/15	8 (53.3%)	3 (20%)	4 (26.6%)
Delta bending angle <i>p</i> = 0.448	< 1	3 (9.7%)	2/3	1/3	0	1	2
	1–10	20 (64.5%)	4/20	10/20	9 (45%)	3 (15%)	8 (40%)
	> 10	8 (22.6%)	2/7	3/7	3 (37.5%)	1	4 (50%)

No significant difference in the patients' clinical outcome was obtained among patients who had different oscillatory frequency and delta bending angle

imaging clues to aid in the diagnoses of TCS [4]. Still, a conus level at L3 is indeterminate, since it is possible for normal or tethered conus to be located at this level. The patients with a surgically proven tethered cord have the conus located at levels ranging from L3 to S4, with the average level of termination at L4–L5 [10, 15, 24].

The spinal cord has physiological movements in all three (anterior, posterior, and lateral) directions [10]. The normal rhythm of the spinal cord is maintained by pulsations of cerebrospinal fluid (CSF) flow, which in turn is maintained by the transmitted cardiac pulsations. Exploiting the physiological movements of the spinal cord, Takiguchi and colleagues tried to measure the shift of the spinal cord in various positions (supine, prone, and lateral) but could not measure the accurate distances in prone position due to motion and pulsation artifact [22]. Winklhofer et al., measured the distance from the vertebral body to anterior border of spinal cord (oscillatory distance) and found that the measurements differed significantly between the scans conducted during breath-holding, normal breathing, and forced breathing. They also found that the effects of respiration and CSF pulsation artifacts decrease at the level of the lower cord [25]. Real-time sonography may be used to detect tethering and retethering. It detects the loss of transverse oscillations of spinal cord. Gray scale (B mode) imaging has been shown to be comparable to MRI in the assessment of TCS [2, 10, 17, 23].

Brunelle et al., proved that the CSF and spinal cord show certain oscillatory motions, and the motion is reduced in patients having a lipoma [3]. Nakanishi et al., studied the use of prone positioning in detecting TCS and concluded that the terminal filum was more posterior and the cauda equina was more anterior on prone MRI in patients with TCS than in healthy individuals [13]. By turning the patient in a prone position, the dynamicity of cord can be better assessed and the exact degree of tethering can be commented upon. Oliver and colleagues highlighted the importance of the prone sequence of MRI in patients in whom retethering occurred. The prone MRI protocol helps in the early detection of these cases [23].

### Significance of various findings in our study

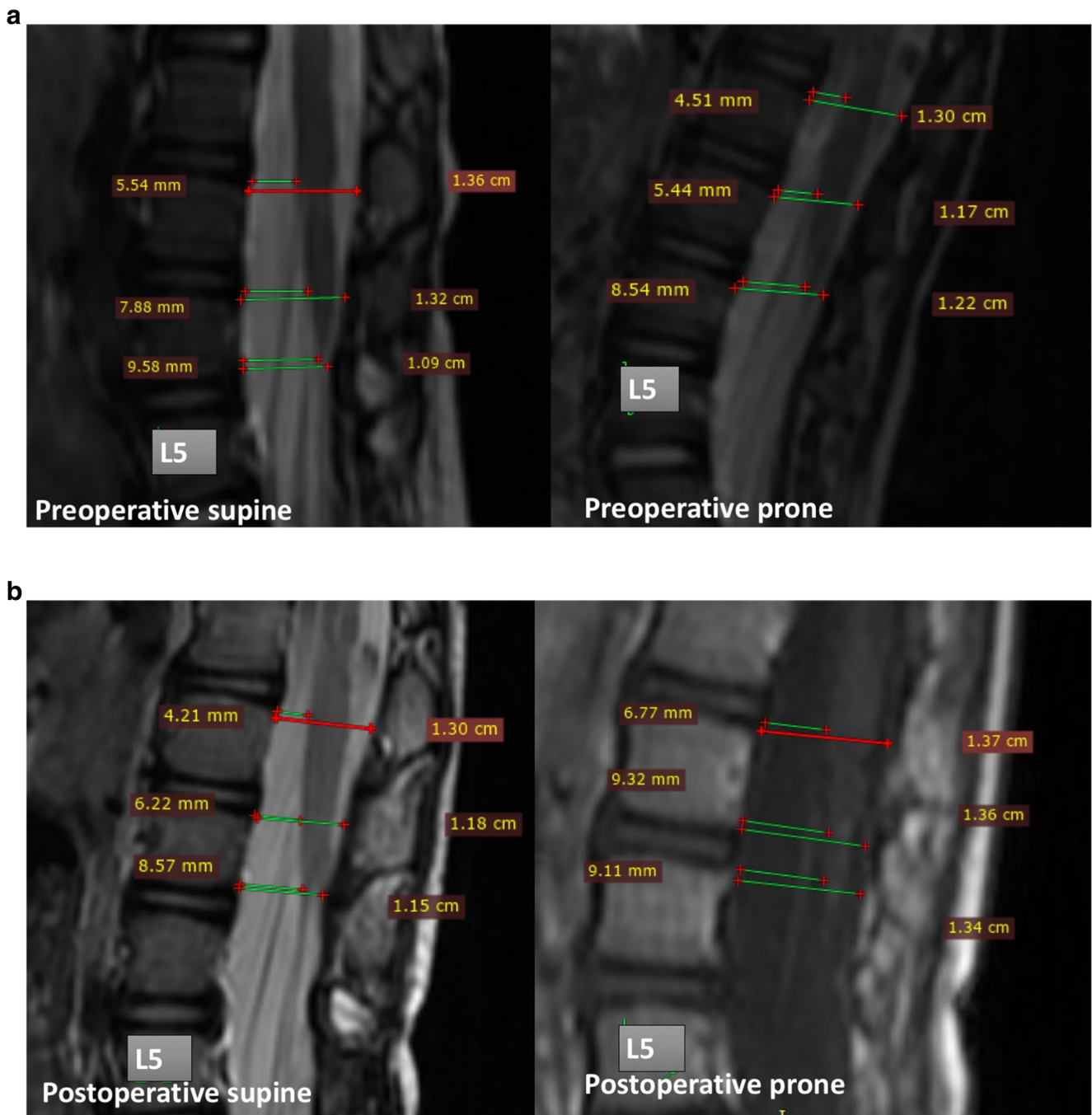
In the control group, we found that the OD in both supine and prone positions, at the index level and two consecutive levels above, was statistically significant [16]. This demonstrates that there is a significant change in the displacement of the lower end of cord when there is a change in the position of the body from supine to prone position [12, 14]. On the contrary, the numerical value of OD in the study group was not statistically significant. Therefore, the cord does not move anteriorly when patients having TCS are evaluated in the prone position.

The difference in the OD between the study and the control groups was found to be significant at the level of conus and one vertebral level above but not at two vertebral levels above the conus tip. This might be because the lower spinal cord is relatively fixed being tethered by the denticulate ligaments and the exiting nerve roots and the canal diameter is also narrower at the latter level. In contrast, the conus is tethered to the posterior dura, thus increasing the relative OD in these patients.

The reduction of OF gives an evidence of stretching as well as posterior attachment of the lower end of the spinal cord [20]. In the postoperative imaging, therefore, assesment of OF in addition to the evaluation of the ascent of cord may provide better information.

Another novel parameter that was introduced was the  $\Delta$ BA. Normally, the longitudinal axis of the conus is aligned with the longitudinal axis of the lower end of the cord, without or with a minimal angulation, present between them. In TCS, due to the stretching and adhesion of the lower end of the cord to the posterior dural surface, a significant measurable angulation is present between the two longitudinal axes, respectively. It was found that the difference in the  $\Delta$ BA was significant among the patients of all the three subgroups.

The lax and long-winding course of the exiting ventral roots becomes straightened due to the stretch and downward displacement of the spinal cord in patients with TCS. This is



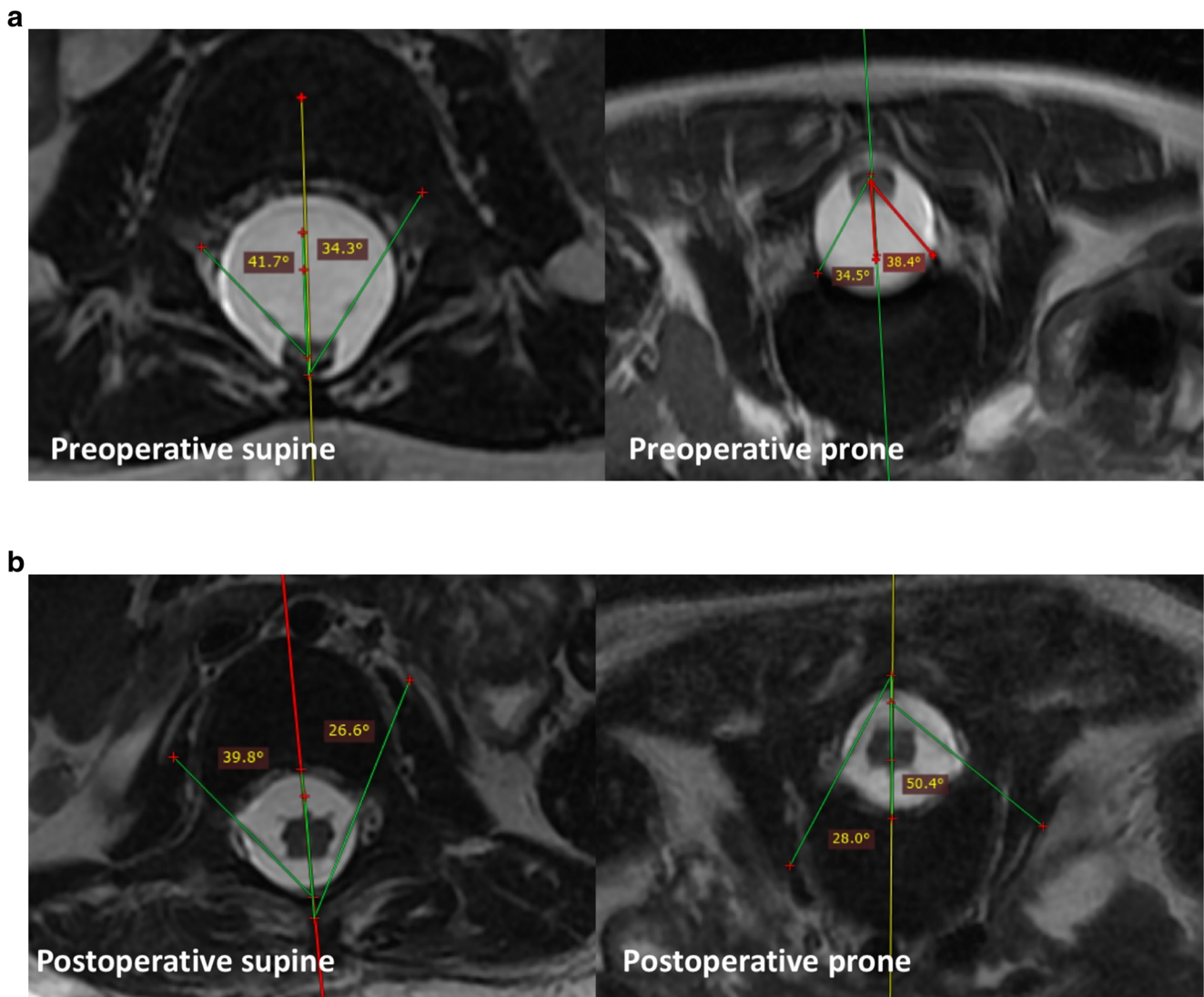
**Fig. 6** Representative sagittal T2W MRI showing calculation of oscillatory frequency by measuring the difference in the ratio of oscillatory distance and spinal canal diameter in the preoperative and

postoperative supine and prone positions at the tip of the conus, as well as the upper border of two contiguous vertebrae above in the preoperative (a) and follow-up scans (b)

apparent in the significant difference in the root angulation obtained on both sagittal and axial MR images at the level of the conus in the study and control groups.

In the subgroup analysis, it was also possible to differentiate between the extent of tethering based on our radiological parameters. According to our study, in the meningomyelocele and the lipomyelomeningocele subgroups, the extent of posterior tethering was much more

compared to the thick filum terminale group and the control group, with the tractional force being directed posteriorly; therefore, the translatory movement (OF) was the minimum in the former two groups. The  $\Delta$ BA also became progressively more acute when one compared the thick filum terminale, lipomyelomeningocele, and the myelomeningocele subgroups. The surgical dilemma of whether or not to detether the spinal cord in these



**Fig. 7** Representative axial T2W MRI showing calculation of axial root angle in the preoperative supine image (**a**) as well as the follow-up scans (**b**) in supine and prone positions of the patient

subgroups, especially when the spinal cord is not below the level of L3, can be objectively resolved using the proposed parameters. Two patients in our series had hydrocephalus, and two had associated Chiari I malformation. There was no apparent difference between the values obtained in these patients when compared to rest of the patients in the series; however, the recruitment of a greater number of patients in these groups would have led to a more meaningful inference.

### Strengths of our study

The emphasis on ratios and differences between the measured findings, rather than on absolute values, overcomes the disadvantages of variability in the measured diameters in the adults and children and between different ethnic groups. The objective definitions provide an easy measurability of the

parameters on routine MRI sequences and their easy reproducibility and comparison by different radiologists. During the prospective study, we discovered a very important additional point that in prone position, the patients, especially children, feel less fearful and claustrophobic while undergoing the MRI scan. We did not objectively assess the claustrophobia level, but definitely observed that the patients in our study were found better compliant while undergoing MRI in a prone position. This has also been the observation in a previous study by Hricak et al. [8].

### Limitations of our study

A larger number of patients in each subgroup would have unequivocally established the statistical significance of the differences in the proposed parameters between the control and study groups, as well as the subgroups evaluated.

However, utilizing non-parametric tests, we obtained an overall significance which was not confounded by age and gender. Our study also revealed a trend between various subgroups responsible for TCS, suggesting that as the degree of tethering increases, the evaluation of spinal cord movements reveals a progressive lesser OF, a greater  $\Delta$ BA, and a greater traction on nerve roots. Inclusion of the postoperative evaluation of these parameters in the radiological assessment following the cord detethering procedure, as well as the study of the parameters obtained on detecting clinical evidence of further retethering of the cord at the follow-up visit and its subsequent detethering, would have comprehensively established the role of our study parameters. The follow-up MRI studies were not routinely performed as continuously repeating an MRI study in the follow-up period translated into a significant economic burden for our patients. A longer follow-up with more number of cases is required to ascertain the relevance of our study parameters on the clinical outcome in patients.

The effect of cardiac and respiratory movements on natural cord pulsations was not eliminated in the study; however, previous studies in literature have shown that their effects are lesser at the lower cord levels, which was the focus of our study [25]. Placing the patient in supine followed by prone position requires additional time, an occasional requirement of sedation especially in children, and relocalization sequencing. In our patient set, we always had an anesthetic backup in the MRI suite, in case it was ever required. None of the patients in our study faced any minor or major complications during the conduction of the dynamic MRI scans. We did not calculate the additional time requirement for the procedure because different technicians performed MRI on different days but estimated that the imaging in prone position only required 5 to 10-min additional sequence acquiring time. Finally, our parameters are not real-time, intraoperative measurements but were obtained on a preoperative MRI evaluation. An intraoperative ultrasonography or an MRI would perhaps be more relevant in obtaining real-time values of OF,  $\Delta$ BA, and root angle. In the future, perhaps software could be developed to evaluate these parameters automatically as a part of the “MRI-based, dysraphic state evaluation protocol.”

## Conclusions

Multiple new MRI-based parameters to establish the evidence of TCS have been defined. Each of them evaluated a different aspect of cord tethering: the OF measured the extent of loss of cord displacement in the supine and prone positions, the  $\Delta$ BA defined the angulation that the longitudinal axis of the conus makes with the plumb line drawn along the longitudinal axis of the lower spinal cord, and the sagittal and axial root angles represent the ventral nerve stretching due to the stretched spinal cord. These parameters will help in defining the evidence

of a stretched cord that is vulnerable to exhibit symptoms of TCS, even when the lower level of cord is not below the conventionally defined level of L3.

**Funding** No funding was received for this research.

## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

**Ethical approval** All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee (Sanjay Gandhi Postgraduate Institute of Medical Sciences, Lucknow, India) and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

**Informed consent** Informed consent was obtained from all individual participants included in the study.

Additional informed consent was obtained from all individual participants for whom identifying information is included in this article.

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