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ORIGINAL ARTICLE

Thoracic kyphosis assessment in postmenopausal women: an examination of the Flexicurve method in comparison to radiological methods

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Abstract

Summary The Flexicurve ruler is an alternative method to radiographs for measuring thoracic kyphosis (curvature), but it is not certain that it is comparable. This study shows that Flexicurve can estimate radiographic vertebral centroid angles with less error than Cobb angles but that its accuracy would be inadequate for most clinical purposes.

Introduction The Flexicurve ruler provides a non-radiological method of measuring thoracic kyphosis (TK) that has moderately strong correlations with the gold-standard radiographic Cobb angle method, while consistently underestimating the TK angle. Cobb angles can include measurement errors that may contribute to poor agreement, particularly in older populations. The vertebral centroid angle could be a better radiographic reference method for the validation of Flexicurve. Using two separate radiographic measurements of TK, we examined the validity of Flexicurve. We aimed to ascertain the level of agreement between measures and to empirically explore reasons for between-method differences.

Methods TK angles determined using Flexicurve and radiographic Cobb and vertebral centroid methods were compared using data from 117 healthy postmenopausal women (mean (SD) age 61.4 (7.0) years). Bland and Altman plots were used to assess differences between methods. Age, bone mineral density and body mass index were examined as characteristics that might explain any differences.

Results Flexicurve angles were scaled prior to analysis. There was no statistically significant difference between angles produced by Flexicurve and vertebral centroid methods (MD − 2.16°, 95%CI − 4.35° to 0.03°) although differences increased proportionally with TK angles. Flexicurve angles were significantly smaller than radiographic Cobb angles and depending on the scaling method used, systematic error ranged between − 2.48° and − 5.19°. Age accounts for some of the differences observed ($R^2 < 0.08$, $p < 0.005$).

Conclusions TK measured using the Flexicurve shows better agreement with the radiographic vertebral centroid method, but inaccuracy of the Flexicurve increases with increasing angle of kyphosis.

Keywords Flexicurve method · Postmenopausal women · Thoracic kyphosis

Introduction

Thoracic kyphosis (TK) describes the curvature of the spine in the sagittal plane between T1 and T12. Normal TK angles are considered to be between 20 and 40° [1], but with advancing age, these angles increase, particularly in women after menopause [2, 3]. The accurate measurement of TK has clinical importance for assessing the physical and functional consequences of TK and risk factors related to its progression. There are a range of options available for the measurement of TK. These can be categorised into radiological and non-radiological methods.

The Flexicurve ruler (Flexicurve) is a simple non-radiological method of measuring TK in the clinic. This flexible length of plastic-coated lead is shaped to the contour of the spine. An outline of this shape is traced onto paper, and measured dimensions are used to calculate either a kyphosis index (KI) or kyphosis angle. It allows clinicians to measure

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TK at low cost and without exposing patients to radiation, making it suitable for repeated regular clinical use. High levels of inter- and intra-rater reliability have been consistently reported for Flexicurve [4–9]. For the purposes of this study, the Flexicurve kyphosis angle was of interest because, and unlike the KI, it provides an angular measure of TK which allows comparison to radiographic measures.

A number of mathematical formulae have been proposed for the calculation of the Flexicurve angle [4, 6, 10–12]. Greendale et al. [4] used geometric formulae to calculate an inscribed angle of kyphosis. By definition, the inscribed Flexicurve kyphosis angle is expected to be smaller than radiographic angles and for this reason requires additional scaling [4] to result in values equivalent to radiographic angles [4]. The scaling metrics suggested by Greendale et al. [4] have, however, yet to be validated in non-hyperkyphotic populations. In addition, these scaling metrics were developed to predict a *constrained* Cobb angle, measured from T4 to T12 and may differ from those required to predict a global Cobb or vertebral centroid angle measured from T1 to T12.

Flexicurve kyphosis angles have been reported to correlate strongly with radiographic Cobb angles, across populations of diverse age ranges (10–96 years old) [4, 6, 8, 9, 12]. Despite a strong correlation, a lack of agreement between Flexicurve and Cobb angles casts doubt over the validity of the Flexicurve as a TK measurement tool [4, 6, 8, 12]. Across populations of varied age and sex, and in those with and without pathology and pain, discrepancies of around 20° are commonly described between Flexicurve and Cobb angles. Reasons for the discrepancies have not been fully explored but could be explained by methodological differences in addition to physical characteristics that may vary between individuals being measured. Body mass index (BMI), for example, can affect the accurate use of Flexicurve in the thoracic [8] and cervical spine [13].

The Cobb angle, taken from a standing lateral radiograph, has a measurement error of less than 5° [14]. However, in some cases, errors associated with duplicate measurements taken by a single rater have been recorded as high as 30° [15]. The Cobb angle is formed by the intersection of lines perpendicular to the superior end plate of T1 and inferior end plate of T12 [16]. In cases where the endplates of these vertebrae (T1 and T12) are affected by degenerative pathologies such as osteoarthrosis or osteoporosis with vertebral fractures, there can be a direct effect on the inclination of the lines used to determine the angle, and therefore the angle itself [14, 17]. A Cobb angle that is influenced by regional deformities at T1 or T12 could overestimate the true TK and this is more likely in older populations [14]. Therefore, Cobb angles may differ from other measures of TK, such as Flexicurve, particularly if these comparisons are made using populations who are older or who have significant pathology affecting the spine.

The vertebral centroid angle is an alternative radiographic assessment of TK advocated for older populations [14]. This angle, also obtainable from a standing lateral radiograph, uses the midpoints of selected vertebral bodies (T1, T2, T11, T12) to measure TK [18]. It is less affected by endplate tilt which potentially makes it a more representative measure of the full contour of the thoracic spine and more appropriate for use over the Cobb angle where pathology or age-related vertebral changes may be a problem. The vertebral centroid angle method has less measurement error and better reliability than the Cobb angle method in measuring the sagittal curvature of the lumbar spine [19, 20]. The vertebral centroid angle method has not previously been compared to the Flexicurve for the assessment of TK in older females where age-related and pathological vertebral changes may be prevalent. Since both the centroid and Flexicurve angles capture the full thoracic curvature and are unaffected by vertebral body abnormalities, the angles they produce could be similar. An improved agreement between Flexicurve and radiographic vertebral centroid angles could help confirm the validity of Flexicurve and may illustrate the limitations of using Cobb angles as the radiographic reference for TK in older female populations.

In this study, we examined the validity of the Flexicurve method using two separate radiographic measurements of TK. The aim was to ascertain the level of agreement between these measures and to empirically explore the reasons for between-method differences using a novel approach. Differences in the physical characteristics of people being measured were reasons of particular interest, but with the potential to influence Flexicurve kyphosis angles, different scaling approaches to calculating this angle were also examined. We hypothesised that Flexicurve angles would show better agreement with vertebral centroid angles than with Cobb angles and that age, bone mineral density (BMD) and BMI may account for some of the between-method discrepancies.

Methods

This was a cross-sectional study with data collected as part of another study examining relationships between physical characteristics and upper back pain in postmenopausal women. Participants volunteered for the study in response to radio and newspaper advertisements as well as social and word of mouth communication. All participants provided written informed consent. The study was approved by the Human Research Ethics Committee at Curtin University (RDHS-267-15). The exclusion criteria for the study were (1) menstruated within the last 12 months, (2) previous thoracic spine surgery, (3) reported systemic inflammatory conditions or neurodegenerative disorders, (4) known pathology of the thoracic spine and (5) previous cancer involving bone.

Participants attended a university-based health clinic on one occasion for measurement of height (cm), weight (kg), BMI (kg/m^2), BMD (averaged bilateral neck of femur (g/cm^2) (dual energy X-ray absorptiometry) and TK using Flexicurve. On a separate occasion, within an average of 7 days, participants attended a local radiological clinic to complete the radiological assessment of TK.

Non-radiological measures of thoracic kyphosis: Flexicurve

A musculoskeletal physiotherapist with over 10 years clinical experience, who had completed over 50 h of practice in using Flexicurve [21], completed the Flexicurve measures of TK. Participants removed all their upper body clothing to expose the spine, and the spinous processes of C7 and S2 were located and marked with a non-permanent pen. The spinous process of C7 was palpated as the most prominent spinous process [22] and S2, by counting downwards from C7. The level of S2 was confirmed as the central point between the left and right PSIS, visually located as skin dimples [23]. Participants stood comfortably upright, while the Flexicurve ruler was placed against the spine from C7 to S2 [24, 25]. The shape of the Flexicurve was traced onto graph paper and the points representing C7 and S2 were joined using a ruled line. The inflexion point where this ruled line crossed the tracing was identified and marked to represent the end of the thoracic length, assumed to be T12 [24]. The widest point between the tracing and the ruled line perpendicular to the thoracic length was identified as the thoracic width. An *inscribed Flexicurve kyphosis angle* (°) was calculated for each participant using the thoracic length (TL) and thoracic width (TW) dimensions and the mathematical formula (TK = arctan (TW/TL1) + arctan (TW/TL2) as previously described [4] and illustrated in Fig. 1. The inscribed Flexicurve values were subsequently scaled to convert non-radiological angles to equivalent radiographic angles [4]. Using a previously developed method, inscribed Flexicurve kyphosis angles were scaled by 1.53 for comparison with Cobb angles (Fig. 1). It should be noted, however, that this method of scaling was developed to produce values equivalent to *constrained* Cobb angles (T4–T12) [4]. The angles calculated using these scaling metrics were therefore referred to in this study as *Flexicurve kyphosis angle (scaled constrained Cobb)*. Additionally, using an equation developed from our own data, inscribed Flexicurve kyphosis angles were scaled to produce an equivalent *global* Cobb angle (T1–T12) and these are referred to as *Flexicurve kyphosis angle (scaled global Cobb*). Also, using our own scaling metrics, Flexicurve kyphosis angles were scaled to produce an equivalent vertebral centroid angle (*Flexicurve kyphosis angle (scaled global centroid*)).

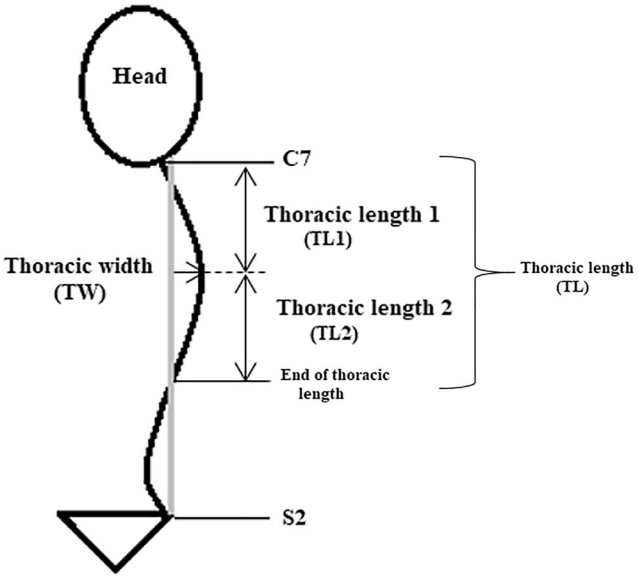

Fig. 1 Flexicurve kyphosis angle. Dimensions used in *inscribed Flexicurve kyphosis angle* calculation (Thoracic kyphosis = arctan (thoracic width (TW)/thoracic length 1 (TL1) + arctan (thoracic width (TW) /thoracic length 2 (TL2) [4]; and *Flexicurve kyphosis angle (scaled constrained Cobb)* calculation (= arctan (TW/TL1) + arctan (TW/TL2) × 1.53

Radiological measures of thoracic kyphosis: Cobb and vertebral centroid methods

Radiographic assessments were completed at community-based radiological clinics of one organisation. Standardised instructions for radiographers were to take a single right-sided lateral thoracic X-ray with the participant's arms flexed to 90°. The X-ray device was positioned at a film focus distance of 120 cm with the beam centred on the mid thoracic vertebrae. The Cobb angle and vertebral centroid angle were determined digitally (InteleViewer, Inteleard, Montreal, Canada) using the same X-ray on separate occasions by a single radiologist (RH) blinded to the aims of the study. Thoracic intervertebral osteoarthritis was judged radiologically as 'nil-mild' or 'moderate-severe'. Thoracic vertebral bodies with a loss in height of ≥ 20% in comparison to normal adjacent vertebrae were recorded as vertebral fractures [26].

1. Cobb method

Cobb angles (°) were measured digitally using the superior end plate of T1 and inferior end plate of T12 as previously described [16]. Images were optimised by adjusting digital window level and by using imaging software filter tools. Where there was obstruction of the T1 due to overlapping soft tissue, the next most superior vertebra visible was used. Where the viewing of T12 was obstructed, the next most inferior visible vertebra was used.

2. Vertebral centroid method

Vertebral centroid angles (°) were measured digitally using a four-segment method (global angle) previously described [18]. Using the two uppermost visible vertebrae (T1, T2) and the two lowest most visible vertebrae (T11 and T12), the corners of each vertebrae (segment) were first digitised and diagonally connected to locate the vertebral body midpoints. The vertebral centroid angle was determined where a line, connecting the midpoints of the upper two segments and a line connecting the midpoint of the lower two segments, intersected (Fig. 2).

Data analysis

Data were analysed using SPSS version 24 (IBM; Chicago, IL).

Flexicurve kyphosis angles were examined according to the method used to calculate the angle. The following Flexicurve angles were reported:

- Flexicurve kyphosis angle (inscribed)—calculated as previously described and not scaled [4]
- Flexicurve kyphosis angle (scaled constrained Cobb)—calculated as previously described and scaled to 1.53 [4]
- Flexicurve kyphosis angle (scaled global Cobb)—calculated using our own scaling metrics (see below).
- Flexicurve kyphosis angle (scaled global centroid)—calculated using our own scaling metrics (see below)

We developed our Flexicurve scaling metrics in a similar manner to that previously described [4] using half (n = 57) of the sample selected using random numbers. To create a scaling equation, linear regression was used with radiographic global Cobb angles as the outcome and inscribed Flexicurve kyphosis angles as the predictor. The beta coefficient and intercept were used in an equation to scale the inscribed Flexicurve kyphosis angles to equivalent radiographic global Cobb angles in the other half (n = 60) of the sample (radiographic global Cobb angle = intercept + (beta coefficient inscribed Flexicurve kyphosis angle). The linear regression procedure was repeated with vertebral centroid angles as the outcome in order to determine a separate equation for scaling inscribed Flexicurve kyphosis angles to equivalent vertebral centroid angles (vertebral centroid angle = intercept + (beta coefficient × inscribed Flexicurve kyphosis angle).

Descriptive statistics were calculated for participant characteristics and for the TK angles obtained using each method. Histograms for TK data obtained using each method were checked for outliers and normality. The mean difference (MD) and 95% confidence interval (CI) were calculated between all paired combinations of the measures, and these were compared using paired-samples t tests. A correlation matrix consisting of the TK data retrieved from each of the three methods was compiled to assess the strength, direction and significance of linear associations using Pearson product-moment correlation coefficients (r). Correlations were interpreted as weak ($r < 0.3$), moderate ($r = 0.3$–0.5) or strong ($r = > 0.5$) [27]. The criterion for statistical significance was set at $p < 0.05$.

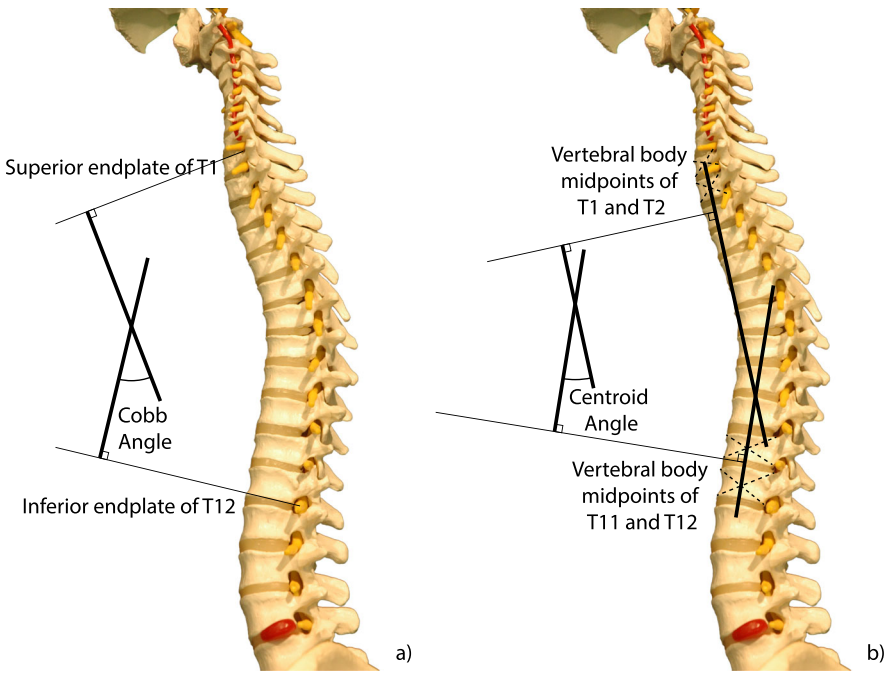

Fig. 2 Radiographic thoracic kyphosis angles. **a**) Cobb angle where the angle formed is between intersecting lines drawn perpendicular to a line level with the superior endplate of T1 and inferior endplate of T12. **b**) Centroid angle formed between intersecting lines perpendicular to a line drawn with reference to the vertebral midpoints of T1 and T2 and line with reference to the midpoints of T11 and T12. Vertebral midpoints were located by digitising the upper right corner of the vertebral body and connecting this to the lower left corner using a diagonal line and repeating this for the upper left and lower right corners. The intersection of these lines represented the vertebral body midpoint

A Bland and Altman method was used to compare TK angles obtained using each method [28]. Flexicurve kyphosis angles scaled to respective global angles were paired with the radiographic Cobb and centroid angles and assessed for agreement by graphically plotting the differences between the measurements of each method for each participant (y-axis) against their mean (x-axis) [29]. A Bland and Altman plot between Flexicurve kyphosis angles scaled to constrained Cobb angles and radiographic Cobb angles was also compiled. The mean difference between the measurements of each method was represented in the Bland and Altman plot with a solid labelled line. Mean differences that deviated from zero indicated a bias [30]. The differences were checked for normality before calculating the 95% confidence intervals of the differences and adding these as the 95% limits of agreement in each plot. The scatter of differences were examined for uniformity around the mean and between the limits of agreement to determine if there was proportional bias and homoscedasticity of differences between measures [31].

Linear regression was used to assess if the differences in measurement between methods were predicted by age (years), BMI (kg/m^2) and BMD (g/cm^2).

Results

One hundred and seventeen postmenopausal women were included in these analyses. Participant characteristics are presented in Table 1. In 69 women, thoracic intervertebral osteoarthritis was absent or mild. The remaining 48 women showed moderate to severe thoracic intervertebral osteoarthritis. Seventeen women had radiological evidence of a vertebral fracture, five of these were located at T12. No vertebral fractures were identified at T1. For the assessment of radiographic angles, T12 was adequately visible in all cases and T1 was sufficiently visible in the majority of cases. For the assessment of Flexicurve angles, the scaling metrics used to convert Flexicurve kyphosis angles into equivalent global radiographic angles are summarised in Table 2.

There was no statistically significant difference between radiographic Cobb and vertebral centroid angles (MD 0.56°, 95%CI − 1.24° to 0.13°), and these methods shared the strongest correlation ($r = 0.94$, $p < 0.001$). Agreement between the radiographic methods was the strongest of all measures examined. A Bland and Altman plot of radiographic Cobb and vertebral centroid angles showed narrow limits of agreement (− 7.89° to 6.77°) and uniformity in the scatter of differences which were tightly clustered around zero (Fig. 3a).

Inscribed Flexicurve angles were the smallest TK angles overall and were significantly different from the angles produced by both the radiographic Cobb (MD 18.02°, 95%CI 16.35° to 19.69°) and vertebral centroid (MD 18.57°, 95%CI 16.99° to 20.17°) methods (Table 1). Correlations were, however, significant and strong between inscribed Flexicurve kyphosis angles and both Cobb ($r = 0.55$, $p < 0.001$) and vertebral centroid ($r = 0.61$, $p < 0.001$) angles.

Table 1 Participant characteristics

	n	Mean	SD	Minimum	Maximum
Age (years)	117	61.4	7.0	46.0	78.0
Height (cm)	117	161.3	6.2	145.8	170.0
Weight (kg)	117	75.3	15.3	42.1	127.2
Body mass index (kg/m^2)	117	29.0	5.5	18.0	47.0
Bone mineral density (femoral neck) (g/cm^2)[a]	115	0.9	0.1	0.6	1.2
Thoracic kyphosis					
Cobb angle method (°)	117	41.7	10.9	17.0	63.0
Cobb angle method (°)	60	40.9	11.3	17.0	63.0
Centroid angle method (°)	117	42.2	10.9	17.0	65.0
Centroid angle method (°)	60	41.7	11.3	17.0	65.0
Flexicurve angle (inscribed) method (°)	117	23.7	5.9	10.9	41.9
Flexicurve angle (scaled constrained Cobb) method (°)[b]	117	36.5	9.0	16.9	64.4
Flexicurve angle (scaled global Cobb) method (°)[c]	60	43.4	5.4	34.1	58.9
Flexicurve angle (scaled global centroid) method (°)[c]	60	43.8	6.6	32.5	62.9

[a] Two missing values

[b] Inscribed Flexicurve angles scaled using metrics created using hyperkyphotic women ($n = 80$) as described by Greendale et al. [4]

[c] Inscribed Flexicurve angles scaled using metrics created using random sample ($n = 57$) from this study

Table 2 Scaling metrics for converting inscribed Flexicurve kyphosis angles into global radiographic Cobb and vertebral centroid angles ($n = 57$)

Flexicurve kyphosis angle calculation method	Beta coefficient	Intercept	R^2
Flexicurve kyphosis angle (scaled global Cobb) method[a]	0.88	22.25	0.21
Flexicurve kyphosis angle (scaled global centroid) method[b]	1.07	17.98	0.31

[a] Metrics calculated from linear regression with global Cobb angle as outcome and inscribed Flexicurve kyphosis angle as predictor

[b] Metrics calculated from linear regression with vertebral centroid angle as outcome and inscribed Flexicurve kyphosis angle as predictor

Using Flexicurve data, scaled using our metrics for equivalent global radiographic angles, linear relationships were strengthened between Flexicurve kyphosis angles and radiographic Cobb ($r = 0.64$, $p < 0.001$) and vertebral centroid ($r = 0.66$, $p < 0.001$) angles. There was no statistically significant difference between vertebral centroid angles and Flexicurve kyphosis angles (scaled global centroid) (MD − 2.16°, 95%CI − 4.35° to 0.03°). In the Bland and Altman plot of these methods (Fig. 3b), limits of agreement were wide (− 18.78° to 14.46°). Proportional bias and heteroscedasticity (unequal variability) were also evident where the scatter in the accuracy of the scaled values increased as the amount of kyphosis increased but in a non-uniform manner.

There was a statistically significant difference between radiographic Cobb and Flexicurve kyphosis angles irrespective of whether global angle metrics or constrained angle metrics were used to scale the inscribed Flexicurve kyphosis angles. For a constrained angle, correlations with radiographic Cobb angles were similarly strong ($r = 0.55$, $p < 0.001$), but the systematic error (MD − 5.19°, 95%CI 3.43° to 6.94°) was higher than for an equivalent global angle (MD 2.48°, 95%CI − 4.77° to − 0.19°). In the Bland and Altman plot of radiographic Cobb and Flexicurve angles scaled to constrained angles (Fig. 3c), the limits of agreement were wide (− 13.61° to 23.99°) and the scatter of differences were non-uniform around the fixed bias of 5.19°. Agreement between radiographic Cobb and Flexicurve kyphosis angles was improved in Bland and Altman plots where Flexicurve data were scaled to global angles (Fig. 3d). This was illustrated by lower fixed bias and narrower limits of agreement (− 19.88° to 14.92°). A proportional bias and mild heteroscedasticity was, however, more noticeable in this plot, where differences increased proportionally and non-uniformly as the average TK angle increased.

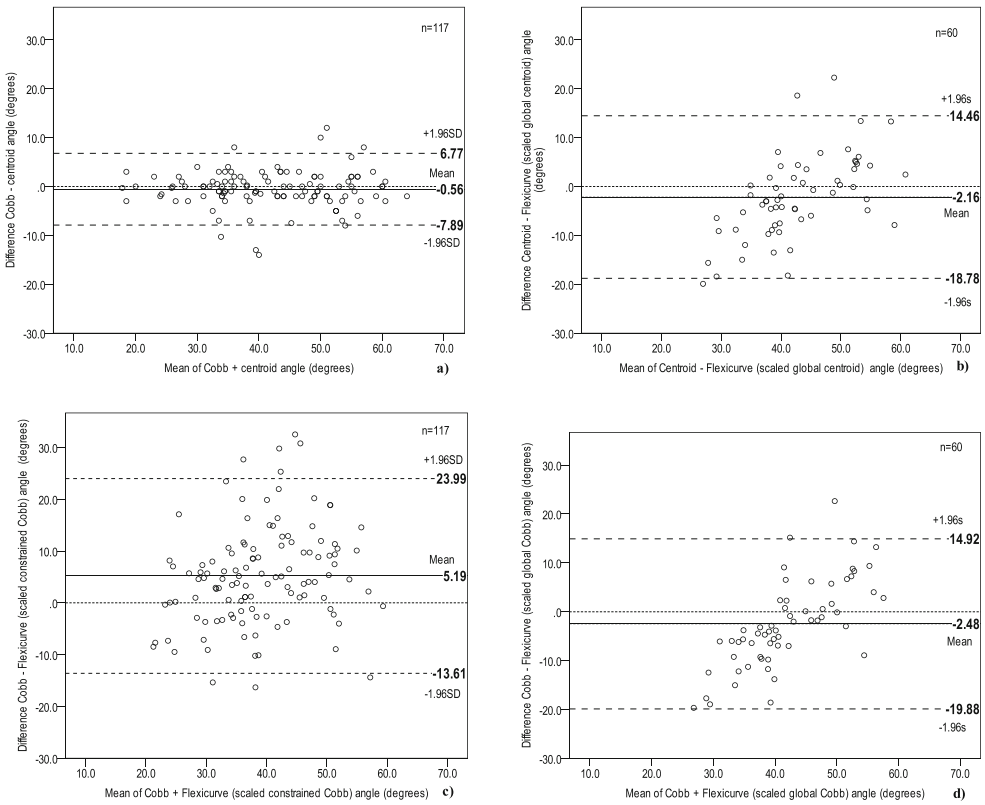

Fig. 3 **a**–**d** Plot of differences against averages for **a**) Cobb and centroid, **b**) vertebral centroid and Flexicurve (scaled global centroid), **c**) Cobb and Flexicurve (scaled constrained Cobb), and **d**) Cobb and Flexicurve (scaled global Cobb). Mean difference (solid line) and upper (+ 1.96SD) and lower (− 1.96SD) limits of agreement (dashed line) are shown

For the methods showing significant differences in TK angles, Table 3 shows which variables contributed to explaining these differences. Of the participant characteristics that were measured, age correlated positively with radiographic Cobb ($r = 0.20$, $p = 0.032$) and vertebral centroid ($r = 0.21$, $p = 0.025$) angles. In contrast, there was a negligible negative correlation with between age and inscribed ($r = -0.04$, $p = 0.691$) and scaled Flexicurve kyphosis angles, irrespective of whether global ($r = -0.02$, $p = 0.691$ ($n = 60$)) or constrained ($r = -0.02$, $p = 0.840$ ($n = 117$)) angle metrics were used. Age was a consistent significant predictor of the differences between inscribed Flexicurve angles and both the radiographic Cobb and centroid methods (Table 3). Age was also a significant predictor of the differences between radiographic Cobb and Flexicurve kyphosis angles when these were scaled to constrained Cobb angles (Table 3). The percentage of variance explained by age in each case was, however, small (< 8%) (Table 3). Body mass index and BMD were not associated with the magnitude of the difference in TK in any of the methods of measurement (Table 3).

Discussion

In this study, we have identified that Flexicurve is unlikely to deliver accurate TK measurements because of the potential for sizeable differences between the TK angles determined using Flexicurve and those measured radiologically, regardless of whether the Cobb or centroid angles are used for comparison. Without scaling, Flexicurve consistently underestimates radiographic TK angles by around 18°, a magnitude that is similar to relevant previous accounts [4, 8]. This would be problematic in clinical contexts where excellent measures of TK are required. The process of scaling does reduce the systematic error of Flexicurve in producing an equivalent radiographic angle, but this varies depending on the scaling method used and the degree of TK. Our data suggest that there is better accuracy in predicting vertebral centroid angles from scaled Flexicurve values but that this accuracy becomes more variable as the degree of TK increases. As a result, there should be caution around interpreting and using scaled Flexicurve kyphosis angles in postmenopausal women who have greater TK.

Several plausible reasons for the disparity in TK measures between Flexicurve and radiographic methods may be considered. First, the Flexicurve may be measuring angles that are fundamentally different to radiographic methods, and the discrepancies noted could reflect a true fault of the Flexicurve instrument. Second, there could be inherent problems in using radiographic Cobb angles to judge the validity of Flexicurve in older populations, and although the Cobb angle is consistently reported as the gold-standard, it may not be the most appropriate radiographic comparator to Flexicurve [32]. Third, the mathematical calculation used to determine Flexicurve kyphosis angles is clearly important, and the scaling metrics used with a geometric formula may be angle (Cobb versus centroid or global versus constrained) and population specific. Finally, participant-specific characteristics such as age, BMD and BMI may influence TK measurements differently [8, 14, 33], and confound comparisons between methods.

In our sample of postmenopausal women, we expected that the vertebral centroid method would be a preferable method to validate TK than the Cobb angle method and the results from our study partially support this. Unlike the vertebral centroid method, the Cobb method can be affected by regional deformities at T1 and T12 [14, 17, 32]. As a result, we hypothesised that there would be poorer agreement between Cobb and Flexicurve kyphosis angles than between vertebral centroid and Flexicurve kyphosis angles. With smaller non-significant systematic error and marginally narrower limits of agreement we observed a subtle improvement in the

Table 3 Predictor variables of the mean differences between methods

Predictor variable	Method comparison											
	Cobb-Flexicurve (inscribed)			Centroid-Flexicurve (inscribed)			Cobb-Flexicurve (scaled global Cobb)			Cobb-Flexicurve (scaled constrained Cobb)		
	$n = 117$			$n = 117$			$n = 60$			$n = 117$		
	R	R^2	p value	R	R^2	p value	r	R^2	p value	r	R^2	p value
Age	*0.251*	*0.063*	*0.006*	*0.274*	*0.075*	*0.003*	0.087	0.008	0.507	*0.245*	*0.060*	*0.008*
BMI	−0.030	0.001	0.749	0.001	0.000	0.992	−0.049	0.002	0.710	−0.063	0.004	0.502
BMD[a]	−0.076	0.006	0.419	−0.063	0.004	0.503	−0.156	0.024	0.242	−0.058	0.003	0.541

BMI body mass index, *BMD* bone mineral density

[a] Two missing values

capacity of Flexicurve to accurately estimate radiographic TK angles using the centroid over the Cobb method. In view of the random error in addition to the systematic error observed when producing equivalent vertebral centroid angles, however, the Flexicurve is still unlikely to be adequate for most clinical purposes. One factor that, in the current study, may have limited us from seeing a clear improvement in agreement between Flexicurve and vertebral centroid angles was the unexpected finding of a near perfect correlation and agreement between radiographic Cobb and vertebral centroid angles. Cobb angles did not appear to be inflated when compared to the vertebral centroid angles, as has been previously observed [14, 32]. In healthy postmenopausal women therefore, these appear to be comparable radiographic measures of TK.

An important finding of our study was the variability in errors that were introduced by using different methods for calculating the Flexicurve kyphosis angle. Previous literature has outlined the need to scale Flexicurve data before comparing it to radiographic angles [4] and we have clearly verified this by showing large systematic errors when inscribed Flexicurve data are used for comparison. We have, however, also highlighted the need for caution around applying scaling factors from one study to another. Scaling metrics suggested by Greendale et al. [4], which were explored as a method for scaling our Flexicurve data, did improve the approximation of Flexicurve kyphosis angles to radiographic Cobb angles by reducing the magnitude of systematic difference. However, despite this improvement, there was no change to the correlations with radiographic Cobb angles and there was still a statistically significant systematic error of − 5.19°. This was greater than the error associated with using our own Flexicurve scaling metrics. Two important aspects of study design may explain why our own scaling metrics provided more accurate estimation of the radiographic angles. First, the formula developed by Greendale et al. [4] was derived from, and proposed for use in approximating, a constrained Cobb angle (T4–T12) which is expected to be lower than a global Cobb angle [4, 14, 18]. Second, the participants of their study were selected to have Cobb angles greater than 40°, so it is possible that the scaling metrics suggested were more specifically for use with participants with greater TK angles than ours.

In contrast to previous accounts [4, 8, 12], our findings show that discrepancies between Flexicurve and radiographic measures vary proportional to the angle being measured. This was evident when using Flexicurve data scaled using our own metrics and those that have been previously developed [4]. Using our scaled data, for example, Flexicurve was likely to underestimate radiographic angles in people with a normal TK (< 40°) and this could be by as much as − 20°. In people with hyperkyphosis (> 40°), Flexicurve was more likely to overestimate radiographic angles, and this could be by as much as 15°. In addition, at greater TK angles, there appeared to be more variability in this pattern (heteroscedasticity) making the Flexicurve a potentially more unpredictable tool for measuring TK in postmenopausal women with greater TK angles. Given that this was a subtle finding in our sample, further data from a more heterogeneous sample, including people with hyperkyphosis, are required to corroborate this. If confirmed, it is possible that a standardised scaling factor would not resolve the errors of Flexicurve in predicting abnormal (> 40°) radiographic TK angles.

In addition to methodological reasons that may explain differences between Flexicurve kyphosis angles and radiographic angles, age, BMD and BMI were also characteristics that were explored. As expected, with such small differences between Flexicurve kyphosis (scaled global Cobb) angles and radiographic Cobb angles, these characteristics did not significantly explain any variance between these measures. Where differences were much larger, for example, between inscribed Flexicurve and radiographic angles, our linear regression established that age was the only characteristic to significantly predict these differences. Of interest was that this was also the case for the differences between radiographic methods and Flexicurve kyphosis angles scaled using the constrained Cobb metrics. In both cases, differences between Flexicurve and radiographic angles increased progressively with age, suggesting that the accuracy of Flexicurve decreases with increasing age using these two approaches. Increases in TK with age may explain this finding [1, 34]; however, our data showed a relatively weak positive correlation between age and radiographic angles to suggest otherwise. Furthermore, in contrast to radiographic angles, Flexicurve kyphosis angles were negatively correlated with age across the sample, regardless of scaling, which could also indicate that the differences with age are explained by the inaccuracies of the Flexicurve. Age accounted for less than 8% of the explained variability in TK between measures, so while this was significant, there are clearly other important factors that determine these differences. Of the other factors that we examined, neither BMI nor BMD were associated with the differences in angles between measures, indicating that these are not physical characteristics with appreciable influence. While every effort was made to ensure that methods were standardised in the present study, we cannot exclude that measurement and methodological factors, in addition to random error, were responsible for the remaining differences.

In summary, the new and novel finding of our study was that the vertebral centroid angle method was a distinguishably better radiographic comparator for the validation of Flexicurve. Although we were able to demonstrate that Flexicurve was better at producing equivalent radiographic vertebral centroid angles, we would still argue that the magnitude of systematic error is larger than ideal for most clinical purposes. Our findings also add to the body of evidence showing that Flexicurve and Cobb angles are related by strong correlation coefficients [4, 6–9, 12]. Our findings have,

however, confirmed previous research [8] in finding a lack of agreement between Flexicurve and Cobb angles, and in doing so, we highlight the limitations of using correlations to assume agreement. While the angles produced by Flexicurve may be conceptually similar to Cobb angles, they appear to be non-uniformly different.

A limitation of our study was that our Flexicurve method was based on a traditional technique where T12 was not formally identified on the Flexicurve at the time of measurement but instead was inferred as the end of the thoracic length from the tracing after measurement. This could be a possible source of error that may have resulted in over- or underestimating the thoracic length dimensions and the Flexicurve kyphosis angle itself. In addition, our Flexicurve kyphosis angles were calculated using one of several possible mathematical angle calculation methods and angles were scaled appropriately for our sample. The two scaling methods that have been compared in this study need further validation using samples with greater TK heterogeneity before deliberating whether Flexicurve is interchangeable with radiographic measures. With the discrepancies in scaled Flexicurve angles far exceeding the 3–11° measurement error associated with radiological methods alone [14, 15], stronger evidence is needed before using Flexicurve in clinical contexts where accurate measures of TK are required. Future studies might also investigate whether the agreement between Flexicurve and radiographic TK angles are improved by using alternative documented calculation methods [6, 10–12].

Although our findings have clearly outlined the limitations of Flexicurve, we acknowledge that there are some clinical circumstances where Flexicurve may still be considered a suitable surrogate measure of TK. In view of the strong correlations with radiographic measures and with Flexicurve measurements previously showing good intra- and inter-rater reliability [4–9], it may still be an appropriate method in clinical situations where the aim is to record change over time, but where the actual measurement is not a key factor. In this context, the benefits to the patient are a robust measure of change without the exposure to radiation.

Conclusion

TK measured in healthy postmenopausal women using the Flexicurve method shows better agreement with radiographic vertebral centroid angles than with radiological Cobb angles. Scaling Flexicurve data is helpful in improving the systematic error of Flexicurve in predicting vertebral centroid angles, but the inaccuracies of the Flexicurve appear to increase and become more variable with increasing angles of kyphosis. Caution is suggested when interpreting TK angles that are determined using the Flexicurve in postmenopausal women, particularly those with greater TK.

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Compliance with ethical standards

All participants provided written informed consent. The study was approved by the Human Research Ethics Committee at Curtin University (RDHS-267-15).

Conflicts of interest None.

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