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RESEARCH

A new human spine model for use in cinematographic gait analysis

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Abstract

Purpose The aim of this study was to compare the accuracy of two spine models: the broken curve model and a new four tangent circles model. The modification concerns the adaptation of data acquisition to kinematic methods used in, e.g., gait and running analysis.

Method Plastic, movable spine model of human with flexible intervertebral disks (manufactured by Erler Zimmer GE3014) was used as the study material. Markers with a diameter of 5 mm were glued to each spinous process (from C_7 to L_5). The recording was performed with a 6-camera Vicon system. Two spine models were created: a broken curve model used, among others, in the Diers scanner, and an own model of 4 circles, similar to the model of circles used in X-ray and CT analysis.

Results The errors in the position of the spinous processes were significantly smaller in the 4-circle model than in the broken curve model. They ranged from 0.01 to 6.5 mm in the lumbar section, from 0.004 to 3.1 mm in the thoracic section. The practical possibilities of using the four-circle model during the cinematographic analysis of gait and run should be checked.

Conclusion The four-circle model is more accurate than the broken curve model and can be used in the cinematographic analysis of the human spine movement.

Keywords Spine curvatures · Spine model · Cinematic method · Four circle model

Simplified models of the human spine are used in the cinematographic analysis of the human spine. Meanwhile, the most accurate image is obtained using Retgon images, computed tomography or magnetic resonance imaging. The most popular method of evaluation is to use the Cobb technique. However, this method is associated with some limitations, mainly related to subjective manual analysis of X-ray images and poor intra- and intergroup reproducibility [1]. Furthermore, each X-ray technique is associated with the exposure of the subject to harmful radiation. In the case of magnetic resonance imaging (MRI), the examination itself takes a long time and has other limitations due to the exposure to the magnetic field. Vrtovec et al. showed that the shape of the spine is best represented by a three-dimensional model based on circles [1]. During automated analysis of CT images, a virtual model spine line is created. The average distances between this line and the position of the center of gravity of the vertebral bodies varied from 1.3 to 2.4 mm depending on the calculation algorithm [2]. The authors further used circles tangent to the spine line for 3D description. These circles can be drawn at any point. Their inverse is called geometric curvature (GC). A 3D model of spinal alignment can be determined by providing GC values at the level of each vertebra. Other studies have also demonstrated the great usefulness of circles for modeling the physiological curvatures of the spine [3, 4].

Non-invasive curvature measurements are characteristic of methods used in posture assessment. Diers formetric

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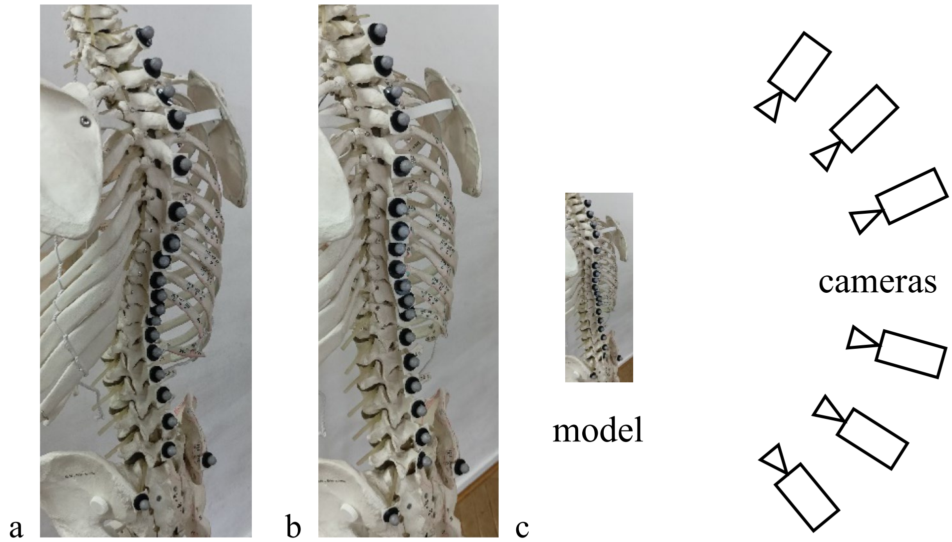

Fig. 1 Marker placement on the skeleton model for the concave-round back curve setting (**a**), flat back (**b**) and camera setup diagram (**c**)

system is based on angular parameters to describe curves. The parameters include the angles of kyphosis and lordosis, which are equivalent to Cobb angles for X-ray images [5–8]. The main advantage of this method is that it is non-invasive and can be repeated several times without harm to the health of the subjects.

However, for the analysis of CT images and body surface scans, the disadvantage is the static nature of the input data in the form of a single spine image or a series of images over a limited period of time. The correct function of the spine depends not only on its alignment but also on its kinematics [9, 10]. It has been shown that many problems with low back pain (LBP) are related to the kinematics of the spine during walking, running, and standing [11–16]. The common feature of this type of analysis is the continuous recording of the trunk kinematics using vision systems, marker systems, or systems based on body surface recording. These tests usually require the recording of several gait or running cycles [9, 10, 17, 18]. The advantage of surface methods is the non-invasiveness of measurements. Therefore, it seems reasonable to implement the spinal models used in X-ray CT and MRI analyses into the surface (vision) motion acquisition methods. Consequently, the aim of this study was to compare the accuracy of two spine models: the broken curve model and a new four tangent circles model, which is a modification of the model proposed by Vrtovec and coauthors [2]. The modification concerns the adaptation of data acquisition to kinematic methods used in, e.g., gait and running analysis. The magnitude of errors in the representation of spinous process positions was used as a comparison criterion.

Material

The research material consisted of 21 cases of video recordings of a human spine model. This was a movable spine model with flexible intervertebral disks (manufactured by Erler Zimmer GE3014). Thanks to this, greater accuracy was achieved in mapping the position of the spinous processes of the vertebrae than in the case of a living person, in whom errors are additionally increased by the presence of skin and fatty tissue. Markers with a diameter of 5 mm were glued to each spinous process (from C7 to L5) using double-sided tape (Fig. 1a, b). The selection of markers and the method of setting up cameras was designed to increase the accuracy of the obtained image and, as a consequence, reduce measuring errors. It has been shown that the use of smaller diameter markers and minimizing the registered area significantly increases the measuring accuracy in cinematographic systems [19]. Additionally, 8 mm diameter markers were glued to the posterior superior iliac spines (LPSI and RPSI). These were markers and measurement points used in standard therapy analysis. The recording was performed with a 6-camera Vicon system (MX3 0.3 megapixel). The cameras were placed at the back of the skeleton at a distance of about 1 m (Fig. 1c). This allowed the minimization of the measuring area at the same time, it was the ability to set the focus with camera lenses. The obtained image has the maximum possible resolution while limiting distortion errors and spherical aberration of the lenses.

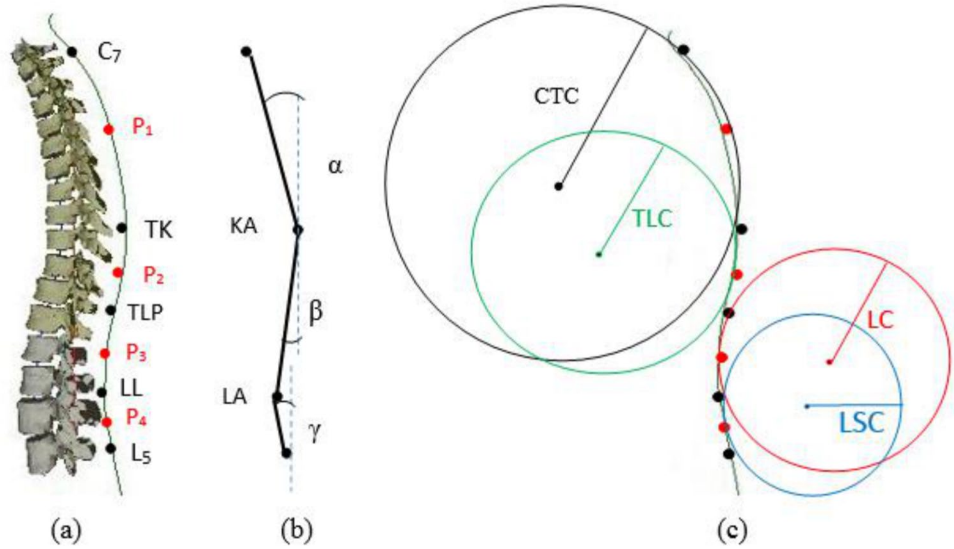

Fig. 2 Positions of markers (**a**; TK—thoracic kyphosis, TLP – thoracic-lumbar transition, LL –lumbar lordosis, P_{1-4} – additional markers), diagram of the broken curve model (**b**; α – angle alpha, β – angle beta, γ – angle gamma, KA – kyphosis angles, LA – lordosis angles), and the diagram of the four circle model (**c**; CTC—cervico-thoracic circle, TLC—thoracic-lumbar circle, L—lumbar circle; LSC—lumbar-sacrum circle)

Method

Twenty-one different settings of the skeleton were recorded, which was bent differently in the sagittal plane each time. This yielded different magnitudes of physiological curvatures of the spine. After each change in the spine alignment, a person experienced in postural assessment identified the position of the main points: the apex of thoracic kyphosis (TK), thoracic-lumbar transition (TLP), the apex of lumbar lordosis (LL) as well as C7, L5 and the posterior superior iliac spines (LPSI, RPSI). Furthermore, the position of intermediate points lying approximately in equal distance between the main points was identified: P1 – between C7 and TK; P2 – between TK and TLP; P3 – between TLP and LL; P4 – between LL and L5 (Fig. 2a).

Data analysis: spine models

A rotation of the external coordinate system was made so that the Ox axis passes through the LPSI and RPSI. Therefore, the analysis of the magnitude of the physiological curvatures of the spine was performed in the Oyz plane (sagittal plane).

The broken curve model was based on the segments connecting the C7, TK, LL, and L5 points. The magnitude of physiological curvatures of the spine was described by means of the following angles: angle γ—the angle between the vertical line and the slope of the segment connecting the spinous process of the first sacral vertebra (S1, alternatively L5) with the apex of the lumbar lordosis (LL); angle β—the angle between the vertical line and the segment connecting the apex of lumbar lordosis (LL) with the apex of thoracic kyphosis (TK); angle α—the angle between the vertical line and the segment connecting the apex of thoracic kyphosis with the spinous process of the seventh cervical vertebra (C7, Fig. 2b). The angle of kyphosis was calculated as the sum of α and β, whereas the angle of lordosis as the sum of β and γ [20].

In the broken curve model, the errors of mapping of the position of each spinous process were calculated as its distance from the straight line representing the given spinal segment (1).

$$\mathrm{Eror}_{\mathrm{broken}} = \frac{\left|Ax_0 + By_0 + C\right|}{\sqrt{A^2 + B^2}} \tag{1}$$

where $(x_0; y_0)$ is the spinous process position point.

and $Ax + By + C = 0$ is the equation of the straight line describing the corresponding spinal segment.

Mapping errors were averaged for C7-TK segment; TK-LL segment; LL-L5 segment. Furthermore, using the definition of a scalar quotient of vectors and the procedure used by Grabara et al. [20], the angles of inclination of particular spine segments in relation to the vertical line (angles α, β, γ), and the kyphosis (KA) and lordosis angles (LA) were calculated.

The four circle model was based on five main points (C7, TK, TLP, LL, L5) and four intermediate points P1 - 4 (Fig. 2c). Based on the above points, the physiological curvatures of the spine were interpolated using a spline function. Cubic (3rd degree) functions available in MATLAB software in the form of a ready-made spline software function were used. Based on the points determined from the interpolation, four circles were described in the corresponding subdivisions using the approximation algorithm. Each circle was determined from the main points, intermediate

Table 1 Median and range of mapping errors of the positions of spinous processes in the broken curve model and the four circle model with significance levels for differences between each other

Error	C_7-TK	TK-LL		LL-L_5
Broken curve [mm]	9.6 min = 7.1 max = 19.3	3.7 min = 0.03 max = 4.8		1.4 min = 0.4 max = 3.1
	C_7-TK	TK-TLP	TLP-LL	LL-L_5
Four circles [mm]	0.6*** min = 0.1 max = 1.9	1.3*** min = 0.004 max = 3.1	0.1*** min = 0.01 max = 1.2	0.6# min = 0.01 max = 6.5

#$p \leq 0.1$; ***$p \leq 0.001$

(C_7–seventh cervical vertebra, TK – thoracic kyphosis, TLP—thoracic and lumbar inflection point, LL – lumbar lordosis, L_5 – fifth lumbar vertebra)

points, and interpolated points. The cervicothoracic circle (CTC) was determined based on C7, P1, TK; thoracic-lumbar circle (TLC)—on points TK, P2, TLP, lumbar circle (LC)—on points TLP, P3 LL, lumbar-sacral circle (LSC)—on points LL, P4, L5. The radii and centers of these circles were determined. The radii represented a simplified description of the magnitude of the individual curvature. The smaller the value taken by the circle radius the greater the curvature. A radius value going to infinity was equivalent to no curvature (straight line). The mapping errors of the spinous process positions were calculated as the differences in the distances of the individual spinous processes from the respective centers of the circles and the magnitudes of the radii of the circles (2)

$$\mathrm{Eror}_{\mathrm{circle}} = R - \sqrt{(x_0 - x_r)^2 + (y_0 - y_r)^2} \tag{2}$$

where $(x_0; y_0)$ is the spinous process position point, R is the radius of the circle and $(x_r; y_r)$ is the center of the circle describing the respective segment of the spine. As in the case of the broken curve, the values of the mapping errors were averaged for individual spinal segments. Eventually received: $\mathrm{error}_{\mathrm{broken}}$ for the three parts of the spine C_7-TK, TK-LL, LL-L_5 and $\mathrm{error}_{\mathrm{circle}}$ for the four parts of the spine C_7-TK, TK-TLP, TLP-LL, LL-L_5. Errors in the following parts of the spine were compared: C_7-TK v. C_7-TK, TK-LL v. TK-TLP, TK-LL v. TLP-LL and LL-$L_{5\text{ v.}}$ LL-L_5. The model that had smaller errors was considered better.

For the mapping errors, no normal distribution was found (Shapiro–Wilk test). Therefore the significance level for the differences between the two types of errors was evaluated using Wilcoxon's nonparametric signed-rank test ($p \leq 0.05$). The statistical significance was set at $p \leq 0.05$. Calculations were performed in MATLAB R2016a, Statistica 13, and Excel 2010 software.

Results

For the broken curve model, the largest errors in the mapping of spinous process positions were found in the C7-TK segment (Table 1). They ranged from 7.1 to 19.3 mm. The smallest errors occurred in the lower lumbar segment (LL-L5; range 0.4–3.1 mm). For the four circle model, in general, these errors were smaller and for the entire spine, they ranged from 0.004 to 6.5 mm.

The significance level for the differences between the mean error values in both models was less than $p = 0.001$ in the case of the following spine segments: C7-TK ($Z = 4.014$; $p = 0.00006$), TK-TLP ($Z = 3.458$; $p = 0.00054$) and TLP-LL ($Z = 3.807$; $p = 0.00014$). There was a trend toward the occurrence of differences for the LL–L5 segment ($Z = 1.917$; $p = 0.55$).

On average, the broken curve model showed a greater magnitude of thoracic kyphosis compared to lumbar lordosis (KA = 35.2 ± 5.51°; LA = 22.9 ± 3.74°). Kyphosis was also characterized by a greater range of variability (about 20°) than lordosis (LAa. 17°; Table 2). In the four circle model, the greatest spinal curvature on average was observed in the C7-TK segment. This was associated with the smallest CTC radius value = 175 ± 14.9 mm. The smallest spinal curvature occurred in the TLP-LL segment (LC = 979 mm, Table 2).

Discussion

In assessing the reliability of new measurement methods and new models, the so-called gold standard is the presentation of Bland–Altman charts. In this paper, this method

Table 2 Medina, minimum and maximum values of parameters describing physiological curvatures of the spine in two models: broken curve and four circle models

	Me	Min	Max
Broken curve model			
α [°]	22.7	13.2	35.0
β [°]	13.0	3.7	23.8
γ [°]	8.8	2.7	18.7
KA [°]	36.5	22.6	42.3
LA [°]	22.9	16.5	33.8
Four circle model			
CTC [mm]	172.8	153	205
TLC [mm]	460.5	58	767
LC [mm]	191.4	103	975
LSC [mm]	213.3	27	541

(α—angle of inclination of the upper thoracic segment relative to the vertical line, β—angle of inclination of the thoracic-lumbar segment relative to the vertical line, γ—angle of inclination of the thoracic segment relative to the vertical line, KA—angle of kyphosis, LA—angle of lordosis, CTC—cervicothoracic circle, TLC—thoracic-lumbar circle, LC—lumbar circle; LSC—lumbar-sacrum circle)

was consciously and deliberately abandoned, because the mapping errors themselves are a measure of the accuracy of the model [21]. In addition, the error rate difference is so great that the Bland–Altman plot method is not recommended.

The results obtained in the present study indicate that the use of circles to describe the magnitude of physiological curvatures of the spine is associated with a smaller error in the representation of the positions of spinous processes than in the case of the broken curve model. The average values of the position errors of the model points with respect to their actual position in this paper are comparable to the three-dimensional model proposed by Vrtovec and coauthors [2] (2 mm). During the analysis of X-ray images, the position of each vertebral body was automatically determined, a model spinal line was drawn, and circles tangent to the line were created. Each vertebra was assigned one circle. The use of this procedure in cinematographic (surface) methods would require a marker to be glued to each spinous process. This would be technically challenging. For the most part, researchers use a less frequent distribution of markers [15, 22, 23]. At the same time, it is known that people differ significantly in the magnitudes of the physiological curvatures of the spine and their length [6–8, 24].

The four circle model proposed in this paper takes into account the individual characteristics of physiological curvature and also solves the problem of using a large number of markers glued on the back of the subject. Fewer markers are also associated with a lower density of markers and this allows for using cameras with lower image resolution or a larger recording area. The consequence is the possibility of long-term recording of the magnitude of physiological curvatures during locomotion. It is possible to apply this procedure in both marker and vision systems. Furthermore, the measurement points used in the four circle method take into account the points used in conventional methods of posture assessment (C7, TK, TLP, LL, L5). This allows for using the broken curve model and, after taking into account the additional points (P1 - 4), expanding to the four circle model. A larger radius of the circle is associated with a flattening of the curvature. A radius going to infinity means a straight spine. Providing four radius values (CTC, TLC, LC, and LSC) indicates the mutual proportions of curvatures of different spinal segments. Moreover, defining the curvatures through four circles allows for the description of the mutual relations between the sizes of the curvatures and each other, which makes it easier to understand the balance of the torso in the sagittal plane. This approach is consistent with the new body balance model proposed by Le Huec et al., [25]. The authors described three body balance cones covering individual body segments: lower limbs, pelvis, lumbar and thoracic spine, and cervical spine with head. Similarly, the four-circle model divides the spine into a circle describing the position of the pelvis and lower lumbar section, a circle describing the upper part of the lumbar lordosis, and two circles describing thoracic kyphosis. Since the research was carried out on an artificial skeleton, the testing of the usefulness of the discussed four circle model for the description of spinal curvature on living material still needs to be continued. Reduction in the size of the circle meant increasing the physiological curvature of the spine.

Two types of difficulties in applying the above model should be pointed out. The first is typical problems associated with data acquisition in kinematic methods, e.g., skin tremor or the choice of signal smoothing algorithm. The second is the importance of correct identification of major points (C7, TK, TLP, LL, L5) by the person applying the markers. This must be the person with experience in conducting posture assessment.

Conclusion

In conclusion, it seems that the four-circle model is more accurate than the broken curve model and can be used in the cinematographic analysis of the human spine movement. Moreover, it is necessary to check the practical possibilities of using the model of four circles during the cinematographic analysis of gait and run.

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Author contribution P.T—conceptualization, methodology, formal analysis, investigation, resources, writing—original draft preparation, writing—review and editing I. P.—conceptualization, methodology, formal analysis, investigation, resources, writing—review and editing R.G.—conceptualization, methodology, formal analysis, writing—original draft preparation, writing—review and editing E.O.—conceptualization, methodology, investigation, resources, writing—original draft preparation, writing—review and editing W.Ch.—conceptualization, methodology, investigation, writing—review and editing A.M.—conceptualization, methodology, formal analysis, resources, writing—original draft preparation, writing—review and editing.

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Data availability No datasets were generated or analyzed during the current study.

Declarations

Conflict of interest The authors declare that they have no conflicts of interest related to the research and publication of this work. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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