A software program to measure the three-dimensional length of the spine from radiographic images: validation and reliability assessment for adolescent idiopathic scoliosis.

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Abstract

Background and Objective: The aim of this study was to validate a new program which aims at measuring the three-dimensional length of the spine's midline based on two calibrated orthogonal radiographic images. The traditional uniplanar T1-S1 measurement method is not reflecting the actual three-dimensional curvature of a scoliotic spine and is therefore not accurate. The Spinal Measurement Software (SMS) is an alternative to conveniently measure the true spine's length. *Methods:* The validity, inter- and intra-observer variability and usability of the program were evaluated. The usability was quantified based on a subjective questionnaire filled by eight participants using the program for the first time. The validity and variability were assessed by comparing the length of five phantom spines measured based on CT-scan data and on radiographic images with the SMS . The lengths were measured independently by each participant using both techniques. *Results:* The SMS is easy and intuitive to use, even for non-clinicians. The SMS measured spinal length with an error below 2 millimeters compared to length obtained using CT scan datasets. The inter- and intra-observer variability of the SMS measurements was below 5 millimeters. *Conclusions:* The SMS provides accurate measurement of the spinal length based on orthogonal radiographic images. The software is easy to use and could easily integrate the clinical workflow and replace current approximations of the spinal length based on a single radiographic image such as the traditional T1-S1 measurement.

Keywords

Adolescent Idiopathic Scoliosis
Early Onset Scoliosis
Spine's length
T1-S1
Height
Software program

1. Introduction

The measurement of body height is regularly used to assess various clinical parameters such as the body mass index, ventilatory vital capacity [1], the normal values of blood pressure in children [2] and the body growth rate. Althought measurements are easily done for healthy subjects, problems arise with patients suffering from scoliosis. Due to the three-dimensional deformation of the spine, the scoliosis necessarily leads to a reduction of the patient's trunk and body height. For those patients, knowledge about the 3D shape and length of the spine is not only critical for the correct estimation of the true patient's body height, but is of high importance for monitoring the growth of the spine. Indeed, the effect of various growth- preserving surgical technique (magnetic expansion control, vertical expandable prosthetic titanium rib, growing rods, anterior tethering, stapling) on the growth of different spinal section (thoracic, lumbar, unfused vs fused) still need to be investigated. Furthermore, the monitoring of the spinal growth is of high relevance for early-onset scoliosis. For example, it has been shown that the growth of the spine and thoracic cage should reach a length of at least 22cm between T1 and T12 to ensure normal pulmonary function [3].

Currently, no tool is able to accurately provide the 3D shape and length of the spine's midline within a clinical environment. Solutions exists, but are either not accurate or not applicable clinically. For example, the traditional T1-S1 approach, which measures the straight distance between the vertebras T1 and S1 on a frontal X-ray radiograph, only provides an estimation of the spine length. Bjure [4], Kono [5], Ylikoski [6] and Stokes [7] developed formulae to compute the differences between the spine length and spine height based on the curvatures of the spine (Cobb angles), but Tyrakowski et al. [8] recently showed that all these approaches are inaccurate (mean error ranging from 4 ± 3 to 10 ± 7 mm). This measurement error can be associated with the main limitation of the measurements; all of which rely on a single frontal radiographic image. With a single image, it is not possible to obtain the three-dimensional length of the spine and therefore its true length is underestimated. In addition, the spine's apparent size varies depending on the position of the patient with respect to the radiographic detector.

To properly measure length on radiographic images, patients must wear a calibration device to accurately compute the pixel size of each radiograph. Without this precaution, it is not possible to quantify the length of a spine on an X-ray image. Alternative 3D measurement devices could be used to determine the true spinal length such as Computed Tomography (CT), Magnetic Resonance Imaging (MRI). These machines provide 3D anatomical details of the spine such as intervertebral disc visualization and the opportunity to measure anterior and posterior length of the spine independently. However, they are not routinely used clinically for scoliotic patients due to increased radiation dosage (CT), cost and time. In addition, these three-dimensional acquisitions are performed in supine position, resulting in a different length measurement than in standing position. The new EOS technology (EOS imaging, Paris, France) allows the simultaneous acquisition of low-dose orthogonal images. Since the position of the patient within the scanner is known, the images provided by this device can be easily calibrated. The device produces high quality images, similar to calibrated orthogonal x-rays, however it is expensive and the measurement of the spinal length remains to be determined. Finally, several studies proposed the use of ultrasound (US) to acquire images of the spine in supine position without exposing the patient to radiation [9]–[11]. For example, the Scolioscan device projects the 3D data of the spine in the coronal plane to accurately measure the Cobb angle of the spinal deformity [12]. However, this tool has not been used to measure the length of the spine nor to directly record the three-dimensional shape on patient's spine. To the best of the authors' knowledge, no US device currently available for clinical application is able to measure spinal length.

For these reasons, the objective of this study was to develop a program – the Spinal Measurement Software (SMS) – to measure the spinal length from clinical radiographic images. The requirements for the program were to be as simple as possible and to enable accurate measurements within a couple of minutes. This study presents the validation of the program regarding validity, reliability and usability.

2. Material & Methods

The spinal length measurement procedure using the SMS is done in three steps (Figure 1). First, a frontal and lateral X-ray image of a patient wearing a calibration tool [13] attached on his/her back is acquired. The calibration tool is a PMMA object with 16 radio-opaque fiducials embedded in a specific 3D arrangement. A turning plate similar to the one proposed in [14] can be used to maintain the patient in the same position on both X-ray images. Second, the user manually locates the position of these 16 reference points on both images to calibrate them [15]. The reference points correspond to the imaged calibration fiducials. Third, the user draws the center midline of the spine on both images. To this end, the SMS provides a deformable spline and the user simply positions a few control points (4 to 6, depending on the curvature) such that the spline cross all the vertebral body centers of interest. . Finally, the 3D reconstruction of the spine's midline as well as the length of the spine is automatically computed and displayed.

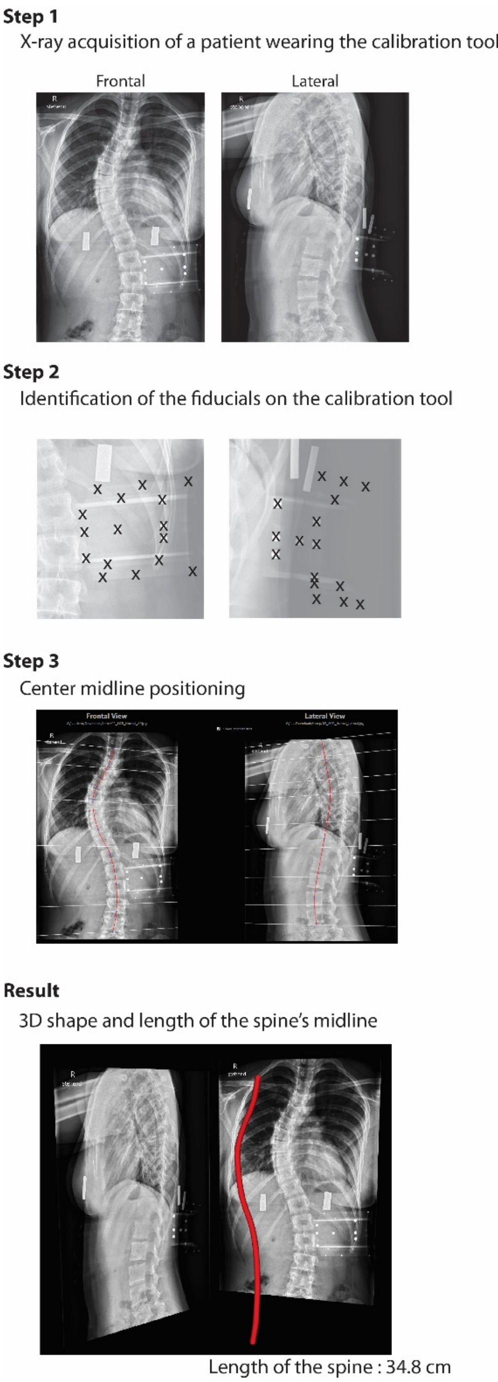


Figure 1: **The workflow of the Spinal Measurement Software shown on a patient's dataset**. The system requires a frontal and a lateral radiographic image of the patient wearing the calibration tool. The 16 reference points of the calibration tool must be identified on both images and the spine midline needs to be defined on both images using a few control points. Finally, the three-dimensional shape and length of the spinal midline is automatically computed and displayed.

To avoid radiation on patients, scoliotic phantoms were used to validate the program. The phantoms were built from CT datasets obtained from five patients suffering from Adolescent Idiopathic Scoliosis (AIS). Following the normal preoperative clinical procedure, CT scans of five patients were acquired by Spinal Orthopaedic Surgeons at the Mater Children's Hospital, (Brisbane, Australia). The use of the historical clinical CT scans for research purposes was carried out in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki for research involving human subjects and was approved by the local ethics committee. For each spine, all vertebrae from T1 to L5 were segmented using the commercial program Amira 5.5 (FEI, Hillsboro, Oregon) by the Paediatric Spine Research Group in Brisbane and only non-identifiable label maps were received for this study (Table 1). A surface mesh of each vertebra was extracted and all vertebrae were linked together by a small cylindrical structure. Once finalized, the surface models were exported as STL meshes and 3D printed (Shapeways, New York – www.shapeways.com) with a strong plastic material (PA2200). These phantoms were used as the baseline for the validation study. CT scans as well as orthogonal radiographic images were acquired for each of the five phantoms (Figure 2A). For the radiographic images, a calibration tool [15] was rigidly attached on each phantom.

		P100	P152	P154	P156	P157
Gender		F	F	F	F	F
Side		R	R	R	R	R
Age		11.2	15.5	19.2	13.0	14.7
Weight [kg]		34	46	67	47	55
Maj Cobb angle [deg]		48	55	67	63	52
Lenke		1B	1A	1A	1A	1B
Apex		T7/8	T9	T10	T9	T8
CT measurement on phantom spines [mm]	Mean	352.7	427.3	407.1	417.1	419.0
	Std	0.5	0.5	0.5	0.4	0.5
SMS measurement on phantom spines [mm]	Mean	350.6	424.9	405.5	415.9	417.0
	Std	1.2	2.1	2.9	3.6	3.2
Error [mm]		2.1	2.4	1.6	1.2	2.0

Table 1: **CT scans of AIS and measurement of their phantom spine's length.** Five AIS female patients scheduled for surgery by Spinal Orthopaedic Surgeons at the Mater Children's Hospital, (Brisbane, Australia) were CT-scanned prior to anterior scoliosis fusion. The non-identifiable three-dimensional segmentation of these datasets were used to print 3D models of five phantom spines. The length of the phantom spine measured with the SMS is compared to the length measured with the CT scans. The SMS is systematically about 2mm smaller than the length measured on the CT. The variation of measurement is very low for the CT (about 0.5mm) and range between 1.2 to 3.6mm for the SMS.

The proposed Spinal Measurement Software is freely available online (www.istb.unibe.ch/research/computational_bioengineering). In addition, the 3D meshes of the spines as well as the radiographic images used for this study are available at the same URL under a creative commons license.

Eight non-clinician participants (1 female and 7 males, 35±8 years old) were enrolled in this study to test the usability and the inter- and intra-observer variability of the developed program. They were asked to fulfill four tasks; i) learn to use the SMS and answer a usability questionnaire, ii) measure each phantom spine's length using CT scans, iii) perform the X-ray calibration on each of the radiographic images and iv) determine the phantom spine's midline on each of the radiographic images.

2.1. Measuring the usability of the program

The first question of this study was to evaluate the usability of the SMS. Each participant had 15 minutes to read a user guide and learn how to use the program. The participants were left alone and neither help nor supervision was provided. After the learning procedure, they were asked to measure the spine's length of two out of the five phantoms and to answer a standard usability questionnaire [16]. The questionnaire consisted of 10 questions (Figure 4) marked from 1 (disagree) to 5 (agree). The mean of each question is used to compute an overall usability score as follows:

$$S = 2.5 \cdot (20 + \sum_{i=1}^{10} Q_i \cdot (-1)^{i+1})$$

A usability score of 100% means the program is absolutely easy and intuitive to use, conversely, a score of 0% means the program is very difficult to use and requires high technical skills. At the end of the session, a supervisor verified that the participants were truly able to use and correctly understand the program.

2.2. Measuring the phantom spine's length based on CT scans

The second task for the eight participants was to measure the phantom's length based on the CT scans. The 3D meshes of the vertebrae were randomly presented on a computer screen and each participant had to pick the center of their upper and lower endplates. This procedure was repeated 8 times per vertebrae. The average position of theses 8 landmarks collected on each endplate was used to define the endplate's center. For each vertebra, the midpoint between the upper and lower endplate's center was defined as the vertebral body center (VBC). The phantom's spinal length was measured as the sum of straight lines starting on the upper endplate of T1, crossing each VBC and ending on the lower endplate of L5 (Figure 2B). As a result, the length of each phantom is measured independently by each of the eight participants. Since phantom's length based on the CT scans are considered as the gold standard measurements, any measurement exceeding ±2.0 standard deviations were considered as outlier and rejected from further analysis. The length corresponding to the mean of the measurements of the eight participants was considered as the true phantom's length. The standard deviation was also calculated to assess the reproducibility of the measurements.

2.3. Measuring the spine's length based on orthogonal X-ray

The third task was the calibration of each radiographic image (Figure 2C). To this end, each participant manually identified the projection of the 16 reference points on each orthogonal image. Since the design of the calibration tool is precisely known, the projections can be used to determine the relative position of the anterior-posterior projection relative to the lateral radiograph. Based on the landmark positions on both projections, the projection matrices were calculated [17]. This step constitutes the *calibration procedure*. The fourth task for the participants was to measure eight times the midline of the spine using the SMS, which is referred as the *midline placement procedure*. The midline of the spine is defined as a continuous curve crossing each VBC, from the center of the upper T1's endplate down to the center of the lower L5's endplate.

Both the calibration and midline placement procedure have an impact on the spinal length measurement. The effects of these two parts of the 3D reconstruction on the phantom's length were quantified independently. The impact of the calibration procedure was evaluated using the independent calibrations performed by the eight users, but with a single midline delineation per patient. The standard deviation was computed to assess the inter-observer variability of the length measurement due to the calibration procedure. The intra-observer variability was quantified to evaluate the impact of the midline placement on the spinal length. For both the inter- and intra-observer variability, the intraclass correlation (ICC) were computed [18]. The mean and standard variation of the SMS measurements were calculated and compared to the length as measured on the CT scans.

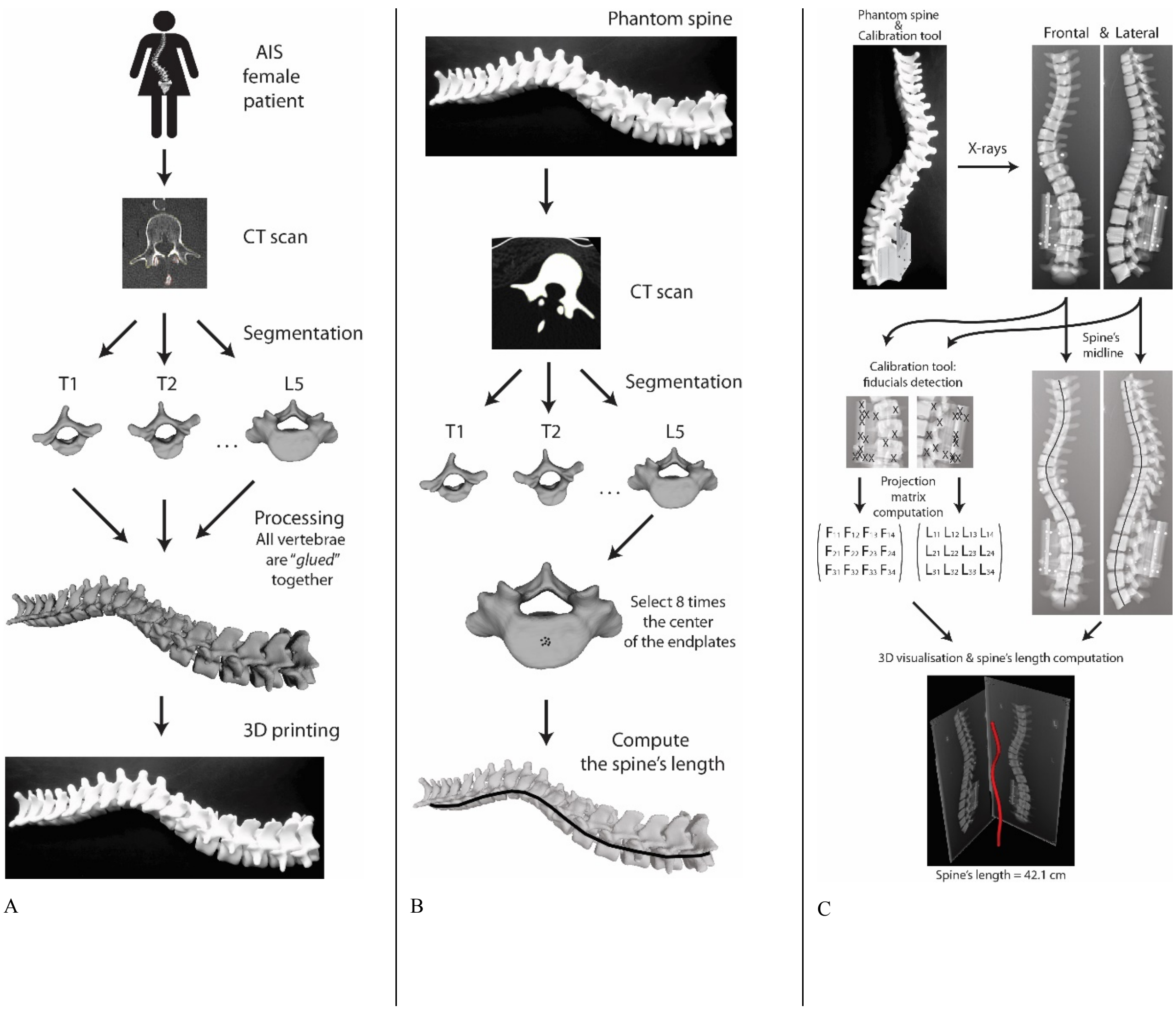


Figure 2: **Measurement of spine's length with phantom spines.** (A) Workflow to produce the phantom spines based on CT from AIS patients. (B) Workflow to measure the phantom's length based on these CT scans. (C) Workflow to measure the phantom's spine using the Spinal Measurement Software.

3. Results

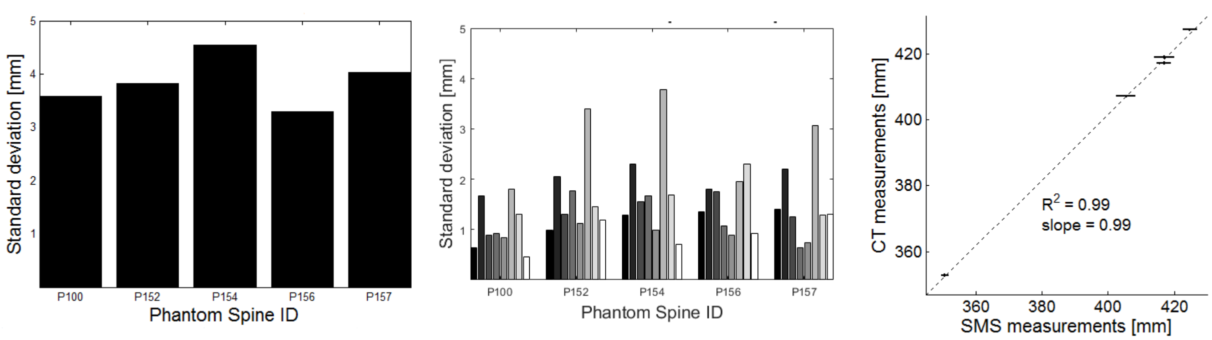
The reference length of the five printed spine phantoms was defined by each user based on CT scan data. Only one single measurement of the phantom length was flagged as outlier over a total of 40 measurements, which represents

2.5% of the data. The standard deviation of the phantom's length was always below 0.6mm (Table 1), which highlights the high reproducibility of measuring the phantom's length based on CT scans.

The effect of the manual calibration on the SMS measurements was quantified. The center of the projected reference points on the radiographic images were picked by each user. All these selections were very close to each other. The standard deviation of the identified center was less than 1 pixel, which represents less than 0.1% of the picture. None of these measurements were flagged as outliers. The standard deviation of the phantoms length obtained with the different calibrations was below 5mm (Figure 3A), and the intraclass correlation is equal to 0.99. In addition, results showed that the difference between the multiple calibrations increases with the distance to the center of the calibration grid. Meaning that accurate measurements were obtained in the pelvic region where the calibration grid was attached to the patient, but larger errors were observed in the thoracic region.

The intra-observer variability was quantified. The variation of the phantom's length due to the midline placement procedure ranged from 0.5 to 3.8mm with a mean of 1.5mm (Figure 3B), which is less than 1% of the complete spinal's length. The intraclass correlation for each participant was 0.99.

The length measurements obtained with the SMS were compared to the ground truth CT measurement. The average measurement error ranged from 1.2 to 2.4mm and the overall mean error between the phantom's length computed with the CT and with the SMS was -1.9mm (Table 1). This result means that the SMS underestimates the true spine length by 0.5%. Linear regression showed a strong correlation between the SMS and the CT-scans (R-squared = 0.99). In addition, the slope of the linear regression was 0.99, which indicates that both methods measure the same length (Figure 3C).



A B C

Figure 3: **Inter- and intra-observer variability of the spine's length measurements.** (A) Inter-observer variability attributed to the calibration procedure has been quantified for each spine. . The variability was almost the same for each spine and ranged from 3.3 mm to 4.5 mm . . (B) Intra-observer variability attributed to the midline positioning procedure was similar across observers and ranged between 0.5 mm to 3.8 mm with an average standard deviation equals to 1.5 mm. (C) The length measured based on CT scans (vertical axis) was compared to the length measured with the SMS (horizontal axis). . The measurements of the SMS correlate strongly with those of the CT-scans (R-squared of 0.99 and a slope of 0.99).

The usability of the SMS was calculated using the subjective questionnaires answered by the users. All the participants were able to learn how to correctly use the SMS and none of them were rejected from the study. Results show that the usability scores of the SMS equals to 89% (Figure 4). Answers from the questionnaire showed that the participants did not find the program unnecessarily complex but rather easy to use without the support of any technical person. Results also indicated that most people learned to use the program very quickly and felt confident using it.

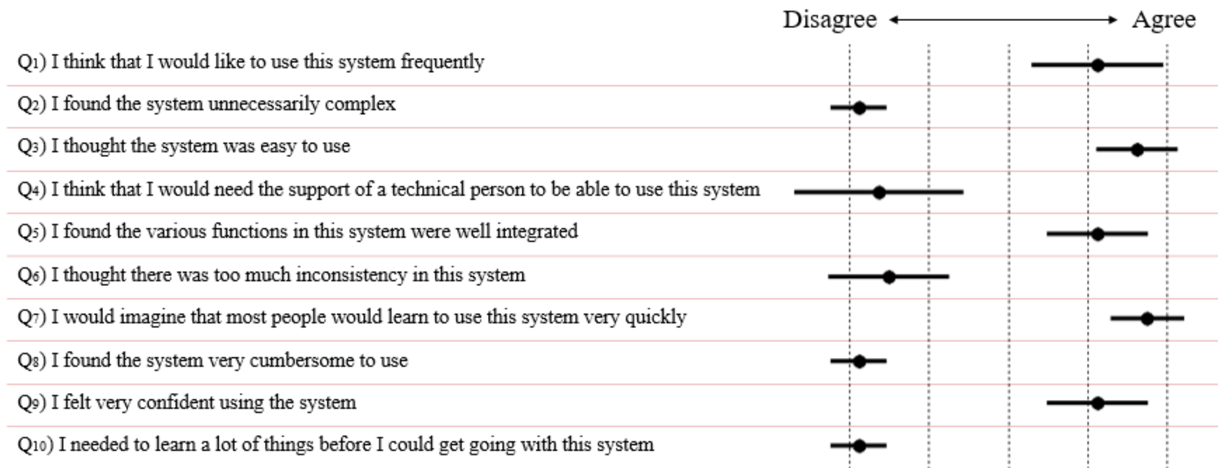


Figure 4: **Usability questionnaire.** Ten questions of the usability questionnaire were answered by each of the eight participants. Values ranging from 1 (disagree) to 5 (agree) were used to calculate the usability score. The mean (dot) and standard deviation (horizontal lines) are shown on the right of each question. The usability score was computed based on the means and equal 89%, which show the program is easy and intuitive to use.

4. Discussion

The objective of this study was to evaluate the validity and usability of a new program – the Spinal Measurement Software – aimed at measuring the shape and length of the spine's midline based on two calibrated orthogonal radiographic images. The program was designed to be usable without specific training and the user was guided through the measurement process using a predefined step by step workflow. Eight users were requested to perform multiple reconstructions of five 3D-printed phantoms using the program in order to evaluate the validity of the measurement, the inter- and intra-observer variability and the usability of the tool.

To the best of our knowledge, no tool is currently available to easily reconstruct the 3D shape of the spine's midline and to measure its length based on orthogonal X-ray measurement. Boivers et al. [19] developed a program to quickly reconstruct the 3D shape of the spine based on an articulated model, but the program is currently not available to clinicians. The sterEOS [20] program comes with the EOS technology and cannot be used to analyze traditional X-rays images. The Keops software [21] does not allow the user to reconstruct the 3D shape of the spine, and therefore cannot measure its length. Finally, the traditional T1-S1 measurement on frontal radiographs cannot give an accurate measurement of the spine's length and cannot be used for spine's growth studies. Other 3D modalities, like MRI, CT-scan and ultrasound, cannot be easily implemented in the clinical routine, due to time and cost issues.

The validity of the spine's length measurement was evaluated by comparing the output of the SMS with the length measured based on a CT-scan and considered as gold standard. Results showed that the length of the spine can correctly be measured with the SMS with a precision of less than 5 millimeters, which represent about 1% error of the spine length. A previous study [22] shows that the spine's growth in adolescent idiopathic scoliosis (from T5 to L5) is about 8mm per year, which is higher than the accuracy of the SMS. However, it would not be possible to measure individual vertebra growth, which is below 1 mm/year. In summary, the SMS allows measurement of the growth of sections of the spine, but cannot accurately measure growth below 5mm.

The variability of the length measurement depends on three main factors. First, the quality of the data during the radiographic image acquisition. Both frontal and lateral images should ideally be acquired simultaneously. Since this is usually not possible in practice, special care should be taken to verify that the patient does not move between both image acquisitions, the shape of the spine must remain constant. In addition, the position of the calibration grid must not be altered between frontal and lateral acquisitions.

Another source of measurement error concerns the quality of the calibration procedure. The calibration was performed manually by the eight participants. All the participants targeted with high reliability the center of each reference point on every radiographic image. Therefore, the variability of the calibration procedure cannot be attributed to the participants, since they correctly performed the task. Actually, the variability of the measurements is on average 2 mm around the calibration tool in the lumbar section of the spine, but increased in the thoracic section of the spine and reached up to 4.5 mm around level T1. Therefore, the calibration tool should be positioned next to the region of interest and toward the middle of the spine, in case the full length should be measured, or should be enlarged to cover the spinal region of interest. Further studies should optimize the design of the calibration grid to limit the inaccuracies introduced by the calibration procedure. In addition, an automatic calibration could help detecting the reference points on the radiographic images, which would improve the repeatability of the measurement procedure.

Results indicated that the approach used to position the spinal midline on the X-ray images has only a limited effect on the overall accuracy. Results show that the variability attributed to the midline placement procedure is generally below 2 mm. Targeting the endplate's center of the upper and lower vertebrae proved to be difficult and is very likely to be a source of variability attributed to the midline placement procedure. To cope with this difficulty, when the user picks a point (i.e. the center of an endplate of a vertebra) in the frontal view, an epipolar line is automatically shown on the lateral view. The user knows that the corresponding point on the lateral view is on this line. This proved to be useful (in pilot testing not included in this paper) when using real patient's radiographic images, because the spine is more difficult to see on the lateral view, due to the higher amount of bone and tissue hiding the spine (shoulder, ribs and lungs). This approach also improves the accuracy of the reconstruction when some vertebras are hidden on the lateral view. Typically, the T2-T5 are hidden by the shoulder and chest in the lateral project. However, the splines used to reconstruct the shape of spinal midline are able to interpolate the missing information. Even if the T2-T5 vertebras are fully removed from the lateral images, the overall error of the length measurement provided by the SMS remains the same (data not shown).

Comparison of the phantom's length measured with the CT-scans and the SMS shows a very good correlation. However, the SMS systematically underestimates the spine's true length by an amount of 1.9mm. An explanation is that the centerlines measured on both modalities do not perfectly match. On the CT scan, the center of the vertebra selected by the user was slightly more anterior than on the radiographic images. This difference is related to the shape of the vertebral bodies, which are curved close to the spinal canal (kidney shaped). However, this three-dimensional feature cannot be seen on radiographs, where the vertebral bodies appear more rectangular. As a result, the spinal midline measured with the SMS is slightly more posterior and shorter. This observation is in agreement with studies showing a length discrepancy between the anterior and posterior side of the spine [23].

The time needed to perform a 3D reconstruction was not precisely monitored during the study. However, the time required to attach the calibration tool on the patient can be estimated to about 1 minute and the image acquisition time is not influenced by the calibration tool. The calibration procedure on the SMS takes about 5 minutes for both images, and the midline placement procedure takes about 1 minute. Therefore, the overall additional time of the measurement corresponds to about 7 minutes per patient. However, the calibration procedure used in this study was completely manual. Future development should automate this step [13], which will significantly reduce the overall measurement time.

The SMS can furthermore be used to assess the loss of height in scoliotic patient. Loss of height is generally estimated as the difference between the spine's length and the spine's height. A recent study [8] showed the inaccuracy of estimating the loss of height based on the Cobb angle [4]–[7]. Since the true length of the spine is measured, the SMS is expected to provide more accurate measurements than the formulas proposed in the literature. In addition, knowing the three-dimensional shape of the spine allows taking into consideration the sagittal profile and not-only the coronal deformity induced by scoliosis.

The purpose of this study was to validate the accuracy of the reconstruction and calculation of the spinal length. Phantoms spines of known length were used, which represent a suitable surrogate spine, but remain a simplification of the real-life image complexity. However, the SMS was designed to be used with real scoliotic patients. Preliminary versions of the software tool were used to measure spinal growth [3] or to assess change of spinal length during standing traction measurements [14], which proved its clinical applicability. In addition, the current version of the software includes epipolar lines that help identifying vertebras on the lateral images, which are of lower quality due to the lungs and rib cage. Moreover, the calibration grid ensures an accurate positioning of the front and lateral images, even if the angle between images is not exactly 90°.

5. Conclusion

The present study shows that the program is intuitive, even for non-experts in the field of medicine and radiography. The accuracy of the program is below 5mm, which is sufficient to measure the global growth of the spine, but insufficient to measure the growth of individual vertebra. Most of the measurement error results from the calibration procedure, while the identification of the spinal midline on the radiographic projection was reliable.

The proposed method could be easily integrated into a clinical workflow, since it only requires a simple calibration tool to be imaged with the patient and the measurement of the three-dimensional length only requires a couple of minutes. We believe that this approach could be used to quantitatively assess the spinal growth, for example in patients with growth stimulating implants like VEPTR [24] or the change in spinal configuration during traction experiments [14], [25].

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