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

Steve Berger [a,*], Carol-Claudius Hasler [b], Caroline A. Grant [c], Guoyan Zheng [d], Steffen Schumann [d], Philippe Büchler [a]

[a] Computational Bioengineering Group, Institute for Surgical Technology and Biomechanics, University of Bern, Stauffacherstrasse 78, CH-3014 Bern, Switzerland
[b] University Children's Hospital Basel, Spitalstrasse 33, PO Box, CH-4031 Basel, Switzerland
[c] Paediatric Spine Research Group, Institute of Health and Biomedical Innovation, Queensland University of Technology, GPO Box 2434, Brisbane 4001, Australia
[d] Information Processing in Medical Interventions, Institute for Surgical Technology and Biomechanics, University of Bern, Stauffacherstrasse 78, CH-3014 Bern, Switzerland

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A B S T R A C T

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.

* *Corresponding author.* Computational Bioengineering Group, Institute for Surgical Technology and Biomechanics, University of Bern, Stauffacherstrasse 78, CH-3014 Bern, Switzerland. Fax: +41 31 631 5947.
E-mail address: steve.berger@istb.unibe.ch (S. Berger).

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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. Although 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 techniques (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 needs 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 22 cm 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 exist, 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) and 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 lengths 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. Materials and methods

The spinal length measurement procedure using the SMS is done in three steps (Fig. 1). First, frontal and lateral X-ray images of a patient wearing a calibration tool [13] attached on his/her back are 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 Reference [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 (4–6, depending on the curvature) such that the spline crosses 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.

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