Three-dimensional visualization and evaluation of musculoskeletal disorders

PhD Thesis

Szabolcs István Somoskeöy, MD

University of Pécs Medical School
Doctoral School for Clinical Medical Sciences
School Director: Gábor L. Kovács, MD, PhD, DSc, FM HAS
Musculoskeletal Clinical Sciences Doctoral Program
Program Director: Péter Than, MD, PhD, Med. Habil.
Tutor: Péter Than, MD, PhD, Med. Habil.

Pécs

2017

This work was partly supported by the following grants of the National Research, Development and Innovation Office:
"3D nyomtatási és vizualizációs technológiákat alkalmazó interdiszciplináris kutatási, oktatási és fejlesztési központ kialakítása a Pécsi Tudományegyetemen" (GINOP-2.3.2-15-2016-00022)
in program "Stratégiai K+F műhelyek kiválósága" (GINOP-2.3.2-15), and
"Sporttal kapcsolatos mozgásszervi elváltozások prevenciója, klinikai kezelése és rehabilitációja, a parasport orvosklinikai aspektusai" (GINOP-2.3.3-15-2016-00031)
in program "Kutatási infrastruktúra fejlesztése – nemzetköziesedés, hálózatosodás" (GINOP 2.3.3.)

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

µm	micrometer
2D	two-dimensional
3D	three-dimensional
ALARA	As Low As Reasonably Achievable, a radiation safety principle and regulatory requirement
AP	antero-posterior
APV	apical vertebra (of the frontal spine deformity)
AVR	apical vertebral rotation, horizontal plane rotation of APV
cm	centimeter
CR	computed radiography
CT	Computed Tomography
DICOM	Digital Imaging and Communications in Medicine, a standard in medical imaging
DR	digital/direct radiography
HKS	hip-knee-shaft
ICC	intraclass correlation coefficient
LAT	lateral
mm	millimeter
MRI	Magnetic Resonance Imaging
PACS	Picture Archiving and Communication System, digitális képarchiváló radiológiai rendszer
SD	standard deviation
SRS	Scoliosis Research Society
US	ultrasound, sonography

1. INTRODUCTION

From early times in Medicine, visualization and evaluation of body structures played a fundamental role in understanding and treatment of musculoskeletal disorders. For centuries, this meant a simple observation and description of external body landmarks. Since 1895, the invention of the X-ray tube and X-ray screen – which had one of the biggest impact in Medicine –, parts of the skeletal system have almost exclusively been studied by two-dimensional (2D) visualization for almost a century. Traditional X-ray imaging still has an eminent role among radiodiagnostic methods, whereas other 2D modalities started to emerge from 1980s for examination of the musculoskeletal system. In previous years, great technical advances have been made in 2D imaging, with magnetic resonance imaging (MRI), computed tomography (CT), ultrasound (US) and nuclear medicine entering routine clinical use. Simultaneously with their becoming established modalities in clinical practice, CT, MRI and US, respectively, the capability of visualization and analysis of orthopedic and traumatological disorders by three-dimensional (3D) reconstructions has been introduced, earning its own place in musculoskeletal diagnostics and research.

Introduction and development of stereo-radiographic methods based on traditional X-ray techniques also started in the 80s of the last century. These usually require aquisition of multi-view X-ray images in two or more dimensions and produce 3D information from 2D projections of objects visible in X-ray images by geometrical, mathematical and statistical methods.

The subject of my thesis is the EOS 2D/3D system, a new and special member of this field, and its role in 3D visualization and evaluation of musculoskeletal disorders.

1.1 The EOS 2D/3D system and EOS 3D reconstruction

French physicist Georges Charpak was awarded the Nobel prize in Physics in 1992 for his research work in detection of atomic particles and his invention and development of the multiwire proportional chamber. This particle detector served a fundamental role in particle research and discovery of new atomic particles in the 70s and 80s of the last century.

The Charpak detector is capable of detection of a single photon while it is insensitive to diffuse, scattered radiation. Digital X-ray images captured by this detector exhibit a wide dynamic range with 30-50 thousand shades of grey and a pixel size of 254 μm. Contrast enhancement similar to the one being used in CT is also available for these images.

The EOS 2D/3D system uses a version of Charpak detector specifically developed for clinical use combined with a series of novel technical solutions. EOS 2D/3D is a low-dose imaging system capable of creating full-body stereo-radiographic images with improved diagnostics due to high quality, excellent contrast images while decreasing patient's radiation dose by 85% compared to a CR or by 50% compared to a DR system. Substitution of specific CT exams with an EOS exam could reduce radiation dose by 95%. Latest development of the system resulted an optional Micro Dose protocol for a further 7-fold decrease in radiation dose.

The EOS device consists of two co-linked pairs of a 45-cm wide linear radiation source and Charpak-detector which are placed perpendicular to each other, in frontal and lateral position. Biplanar X-ray images are simultaneously captured by a slot-scanning method during a synchronized vertical movement of the X-ray tube-detector pairs emitting two perpendicular, 1.8 mm-thin slightly fan-shaped X-ray beams. During this vertical scan, a 170 cm high and 45 cm wide area is covered, producing AP and LAT X-ray images within just 10-25 seconds, of patients in an upright standing (or sitting) position. Detector advantages are further enhanced by double collimation with two 0.5 mm copper collimators inside each X-ray tubes and detectors, for an additional improvement in image quality. The spatially calibrated, simultaneous capture of biplanar images with distorsion-free, 1:1 scale objects enables precise three-dimensional reconstruction of pelvis, vertebrae, lower limbs and other parts of the skeletal system with sterEOS stereo-radiographic software.

The sterEOS 3D reconstruction is based on elements of a generic geometric 3D model library (with T_1-L_5 vertebrae, femur, tibia and pelvis) and uses stereo-radiographic methods of geometrical, parametrical and statistical models. It represents an integrated version of hibrid stereo-radiographic 3D reconstruction methods, producing a parametric surface 3D model. Automatic measurement of clinical parameters is carried out by preprogrammed calculations and data are exported in standard spreadsheet formats with images of reconstructed 3D models separetaly, or overlaid to the original X-ray images.

2. OBJECTIVES

2.1 Application of the EOS 2D/3D system for 3D evaluation of adult lower limb deformities

Our principal objective was making the EOS 2D/3D procedure and its 3D reconstruction method to become an integral part of our lower limb orthopedic activity. More precisely, the radiological examination of most adult patients with lower limb (i.e., hip and knee) complaints presented to our Clinic was aimed to be carried out by lower limb examinations with the EOS 2D/3D system. Lower limb 3D reconstructions from biplanar EOS images to be produced and analysed in everyday clinical routine.

Furthermore, EOS 3D lower limb parameters were planned to be evaluated and compared to published 2D values, in healthy adults and patient groups with hip and knee arthritis.

2.2 Application of the EOS 2D/3D system for evaluation of lower limb fractures after osteosynthesis

This study was done in collaboration with the Department of Traumatology and Hand Surgery. Application of the EOS 2D/3D system was aimed to be evaluated for routine radiological imaging of femur and tibia fractures after osteosynthesis. 2D and 3D values for axis lengths, mechanical angles and torsional parameters of the operated limbs obtained by EOS 3D reconstruction were planned to be recorded and compared to parameter values of the contralateral healthy side.

2.3 Application of the EOS 2D/3D system for pre- and postoperative evaluation of spinal deformities

Our other principal objective was making this new radiodiagnostic procedure and its 3D reconstruction method to become an integral part of our clinical activity related to spinal deformities. More precisely, the radiological examination of most patients with spine deformities and spinal column disorders presented to our Clinic was aimed to be carried out by full-spine examinations with the EOS 2D/3D system. Full-spine 3D reconstructions from biplanar EOS images were to be produced and analysed in everyday clinical routine.

Moreover, postoperative assessment of patients that underwent surgical correction was also to be performed, and 3D reconstruction of postoperative EOS images to be carried out, as well, as part of the standard clinical procedure.

2.4 Evaluation and validation of EOS reconstructions for 3D characterization of spinal deformities

Validation of EOS 3D reconstruction parameters for evaluation of frontal and sagittal curves

The aim of this study was to perform a retrospective validation of EOS 3D reconstruction parameters in a non-randomly selected patient group. Frontal and sagittal curve values measured by sterEOS software were compared to values obtained with conventional manual curve measurement methods. Accuracy and reproducibility of EOS 3D reconstruction measurements were also evaluated.

Evaluation of horizontal plane view images of the EOS 3D reconstruction

With respect to the lack of known adaptable methods in the literature, our aim was to introduce a new nomenclature and establish a minimum semi-quantitative method for evaluation and interpretation of horizontal plane view images of the EOS 3D reconstructions, to be routinely used for general assessments and for comparison of pre- and postoperative images of surgically corrected cases.

2.5 Analysis and validation of vector-based visualization of EOS reconstructions for 3D characterization of spinal deformities

For the visualization, assessment and evaluation of complex horizontal plane view images of EOS 3D reconstructions implementation of a simplified depiction was aimed, which while preserving information for vertebral size, 3D position and orientation, as well as axial rotation, and similarly to horizontal plane topview images of EOS reconstructions, relative vertebral positions to the pelvis could also be quantified.

Additionally, the extendibility of the method to the frontal and sagittal plane views was also expected, in other words, to introduce a truly 3D solution.

Validation of vertebra vector-based parameters for frontal and sagittal spinal curve measurements

By using a methodology identical to the validation of EOS 3D reconstruction parameters, a validation study was to be performed for vertebra vector-based frontal and sagittal spinal curve measurement values, with comparison to values obtained with conventional manual curve measurement methods. Evaluation of accuracy and reproducibility of the measurement values was also carried out.

Application of vertebra vectors for evaluation of deformity progression and results of surgical correction

With the ability of the vector-based method for visualization and quantitative parametric evaluation of spinal geometry, suitability of the new method was analysed for evaluation of spinal deformity progression and for comparative assessment of postoperative results after surgical correction.

Special emphasis was given to examine the relationship of the change in frontal deviation magnitude – conventionally used for evaluation of progression and results of surgical correction – with changes in values of vector-based parameters, especially in the horizontal plane.

3. PATIENTS AND METHODS

3.1 Patient groups

Patients in adult orthopedic lower limb examinations

The normal study group consisted of 65 individuals (36 females, 29 males) with no major joint pathology and no clinical complaints or radiological signs of lower limb degeneration. The average age was 26.3 years (19-39 years range). This resulted a total of 128 normal lower limb 3D reconstructions, due to the exclusion of two right limbs of two females for inaccurate limb positioning on LAT X-rays.

37 patients (29 females, 8 males) suffering from hip arthritis with an average age of 67.8 years (45-80 years range) were included in the hip arthritis group. Since in 16 cases both hips were affected, a total of 53 hips were examined.

32 patients (with a 28/4 female/male ratio) suffering from knee arthritis with an average age of 67.0 years (53-80 years range) were included to the knee arthritis group. Since 18 of the 32 patients were affected unilaterally, a total of 46 knees were studied.

Patients in examinations after osteosynthesis of lower limb fractures

30 subjects were selected from patients who underwent osteosynthesis of lower limb fractures at the Department of Traumatology and Hand Surgery between 2009-2010. Three subgroups were made based on the localization of fractures: pertrochanteric (n=10), femur diaphysis (n=8) and tibia diaphysis (n=12). Gender ratio was 18 females and 12 males with an average age of 48.2 years (24-63 years range).

Patients in validation studies for spinal 3D reconstructions

A total of 201 subjects selected from patients examined at our Spine Deformity Outpatient Clinic between July 2007 and September 2009 were included in this non-randomized retrospective study. The group consisted 170 females and 31 males with an average age of 19.88 years (SD=±10.14), and included 10 young healthy athletes, 175 adolescents with idiopathic scoliosis, 11 adults with degenerative scoliosis and 5 adolescents with Scheuermann disease.

According to objectives *2.4* and *2.5* members of this group were assigned into subgroups based on the magnitude of frontal spinal curves as follows: 0-10° (subgroup no. 1, n=36), 10-25° (subgroup no. 2, n=25), 25-50° (subgroup no. 3, n=69), 50-75° (subgroup no. 4, n=49), and above 75° (subgroup no. 5, n=22).

Patients in studies for evaluation of spinal deformity progression and results of surgical correction

Five of the original 201 group members were selected for analysis of spinal deformity progression (as outlined in objective *2.5)*, based on their examination with the EOS 2D/3D system a total of 11 times with at least 3 months between consecutive visits.

Additionally, postoperative EOS 2D/3D examinations of 95 of the original 201 group members with adolescent idiopathic scoliosis who underwent spine correction surgery were also analysed according to goals outlined in objective *2.5*. This 95 patients (87 females, 8 males, average age of 18.6 years (SD = ± 7.41)) were assigned into subgroups according to the Lenke classification of spine deformities: Lenke type 1: n=30, Lenke type 2: n=1, Lenke type 3: n=36, Lenke type 4: n=2, Lenke type 5: n=14 and Lenke type 6: n=12.

3.2 Study procedures

All radiological examination included simultaneous, biplanar X-rays in an upright position of patients, performed with the EOS 2D/3D system (EOS Imaging S.A., Paris, France).

EOS biplanar X-ray images were stored by the institutional PACS system (Aspyra AccessNET v.6.2, Aspyra LLC, Westlake Village, CA, USA). EOS 3D reconstructions of lower limbs, spine and pelvis based on EOS biplanar images were performed, as outlined in *Chapter 3.3*. Clinical parameters of 3D models of lower limbs, spine and pelvis were automatically calculated and saved by sterEOS software.

Standard lower limb examination procedure

For optimal separation of individual bones of the two limbs in LAT X-rays, a specific leg positioning was used, with the right foot shifted ahead by 8-10 cm. To prevent motion artifacts on X-rays, patients may have held on to handlers inside the EOS gantry.

Orthopedic lower limb EOS examinations were performed the same day of the Outpatient Clinic visit, and trauma patients were imaged 6 weeks–6 months after osteosynthesis.

Standard full-spine examination procedure

For optimal visualization of thoracic vertebrae and to avoid interference from upper limb contours in LAT X-rays, a specific arms positioning was used with elbows elevated ahead of the trunk, bended to 30-40 degrees and fingers touching the face. For patients undergoing surgical correction, full-spine EOS examinations were performed 2-3 weeks before and 3 days after the operation.

Additional steps in validation studies of spine deformities

In validation studies for objectives *2.4* and *2.5,* conventional manual measurements of spinal curves were also carried out using EOS biplanar X-rays. For coronal deviations the Cobb's method, for sagittal curves the modified Cobb's method was used. For an additional part of objective *2.5*, sagittal wedging of lumbar L_5 vertebrae was also measured by conventional methods in LAT X-rays. For manual measurements, a digital Cobb's angle tool of the workstation software of the institutional PACS system (Aspyra AccessNET MedView v.6.2, Aspyra LLC, Westlake Village, CA, USA) was used.

Statistical analysis considerations

Data were processed using SPSS statistical package (SPSS v16.0, IBM Corp., Armonk, NY, USA) in every study. Results were accepted statistically significant, i.e., valid, when statistical error limits were within 5% ($p < 0{,}05$). Mean values of results were presented with their double standard deviation or 95% confidence intervals.

3.3 EOS 3D reconstruction procedure

3D reconstructions were performed by using sterEOS software versions officially supported by the manufacturer, uniformly within each study group: sterEOS v1.3.4.3740 for full-spine, and sterEOS v1.4.2.4850 for adult orthopedic and postoperative traumatological lower limb examinations.

Lower limb 3D reconstruction procedure

Lower limb 3D reconstructions could be performed by two distinct methods in sterEOS, differing in complexity and time requirement: "3D Lower Limb Alignment" (or "fast 3D") and "3D Lower Limb Modelling" (or "full 3D"). The former process is ultra fast, requires 2-3 minutes only, and provides measurements of true 3D lengths and knee parameters. Latter produces, with manual interaction from the operator, a complete surface 3D model of lower limb bones and provides values for all relevant clinical parameters of the model. The method of "full 3D" was used for every study.

In the process of "full 3D" reconstruction of lower limbs, registration of predefined anatomical landmarks of pelvis, femur and tibia in AP and LAT EOS X-rays is followed by further manipulations of reference points for modifications of the initial 3D solution by sterEOS. Consecutive non-linear deformations resulting in length, diameter and shape changes of the 3D model are performed until contours of the 3D model are brought to fit visible bone contours in the X-rays. This process typically requires 8-10 minutes per limb.

Visual evaluation of completed 3D reconstructions was routinely done using frontal, sagittal and horizontal plane views of the 3D model and overlaid to AP/LAT X-ray images.

Clinical parameters of the lower limb and pelvis are automatically calculated by predefined algorithms within sterEOS using the completed 3D model. Due to the inclusion of pelvic anatomical landmarks to the 3D reconstruction process, true 3D values of clinical parameters are calculated relative to the frontal reference plane passing through both acetabular centers ("Patient Plane[1]"). List of lower limb 3D reconstruction parameters in sterEOS is shown in *Table 1*.

Table 1. List of lower limb 3D reconstruction parameters in sterEOS software

pelvic parameters	
pelvic incidence (°)	angle on the sagittal plane between the normal of the sacral plate and the line linking the center of the sacral plate to the center of the inter-acetabular axis
sacral slope (°)	angle in the sagittal plane between the sacral plate and the horizontal
pelvic tilt (°)	angle in the sagittal plane between the straight line linking the center of the sacral plate to the center of the inter-acetabular axis and the vertical
pelvic obliquity (mm)	difference in height between acetabula summits
axial rotation of pelvis (°)	angle between the projections of the inter-acetabular axis and the EOS frontal plane along a strictly horizontal plane

lower limb parameters	
femur length (cm)	length of the femoral mechanical axis
tibia length (cm)	length of the tibial mechanical axis
total length (cm)	length of the global mechanical axis
femoral head diameter (mm)	diameter of the femoral head, assuming an ideal oval shape
femoral offset (mm)	distance between center of femoral head and the orthogonal projection of this point on the proximal diaphysis axis
neck length (mm)	length of femoral neck axis defined by the center of the femoral head and the intersection with the diaphysis axis
neck-shaft angle (°)	angle between the axis of the femoral neck and the femoral anatomical axis
knee valgus/varus angle (°)	angle between the mechanical axis of the femur and the mechanical axis of the tibia in the frontal plane, its value is negative in varus and positive in valgus
knee flessum/recurvatum (°)	angle between the mechanical axes of the femur and the tibia in the sagittal plane, its value is negative in recurvatum and positive in flessum
mechanical femoral angle (°)	angle between the mechanical axis of the femur and the tangent to the distal parts of the condyles in the frontal plane
mechanical tibial angle (°)	angle between the mechanical axis of the tibia and the tangent to the tibial plates in the frontal plane
HKS (hip-knee-shaft) angle (°)	angle between the mechanical and anatomical axes of the femur in the frontal plane
femoral torsion (°)	angle between the femoral neck axis and the posterior bicondylar axis projected in the orthogonal plane of the mechanical axis of the femur; its value is positive in anteversion and negative in retroversion
tibial torsion (°)	angle between the axis tangent to the posterior part of the tibial plates and the bimalleolus axis projected in an orthogonal plane to the mechanical axis of the tibia; its value is positive in external rotation and negative in internal rotation
femorotibial rotation (°)	angle between the posterior bicondylar axis and the axis tangent to the posterior part of the tibial plates projected in the orthogonal plane of the mechanical axis of the femur; its value is positive in tibial external rotation and negative in tibial internal rotation relative to the femur

---

[1] Patient Plane: the patient's personal frontal plane during EOS examination, independently of its relative position to EOS Radio Plane; Radio Plane: main frontal plane perpendicular to EOS AP and parallel to EOS LAT X-ray direction

Spine 3D reconstruction procedure

Spine 3D reconstructions could also be performed by two distinct methods in sterEOS, differing in automation and time requirement: "fast 3D" or "full 3D". The method of "full 3D" was used for every study.

In this process, registration of predefined elements and anatomical landmarks including the sacrum plateau, acetabula, upper endplate of T_1 vertebra and lower endplate of L_5 vertebra, as well as drawing an S-shaped 3D cylinder tracing the shape and width of the spine are followed by the generation of an initial 3D solution by sterEOS consisting of vertebrae T_1- L_5. Using a series of color-coded reference points for translation, rotation and shape/size alteration of each vertebra of this initial 3D model, manual interactions and non-linear deformation of vertebral contours could be achieved. Consecutive interactive modifications of each vertebra are performed until contours of the virtual 3D model are fitting to visible vertebral contours in the X-rays. This process typically requires 20-30 minutes per spine.

Visual evaluation of completed 3D reconstructions was routinely done using frontal, sagittal and horizontal plane views of the 3D model and overlaid to AP/LAT X-ray images.

Clinical parameters of the spine and pelvis are automatically calculated by predefined algorithms within sterEOS using the completed 3D model. Due to the inclusion of pelvic anatomical landmarks to the 3D reconstruction process, true 3D values of clinical parameters are calculated relative to the frontal reference plane passing through both acetabular centers ("Patient Plane[2]"). List of spine 3D reconstruction parameters in sterEOS is shown in *Table 2*.

Table 2. List of spine 3D reconstruction parameters in sterEOS software

pelvic parameters	
identical to parameters shown in Table 1	
scoliosis parameters	
Cobb's angle (°)	the angle in the frontal plane between the upper plate of the upper junctional vertebra and the lower plate of the lower junctional vertebra
apical AVR (°)	axial rotation of the apical vertebra in the Patient or Radio Plane
sagittal balance	
T_1-T_{12} kyphosis (°)	angle on sagittal plane between upper T_1 plate and lower T_{12} plate
T_4-T_{12} kyphosis (°)	angle on sagittal plane between upper T_4 plate and lower T_{12} plate
L_1-L_5 lordosis (°)	angle on sagittal plane between upper L_1 plate and lower L_5 plate
L_1-S_1 lordosis (°)	angle on sagittal plane between upper L_1 plate and lower S_1 plate
spinal orientation	
from T_1 to L_5 (°)	frontal/lateral/axial rotations defining the position of the vertebra in relation to the preceding vertebra through successive rotations defined locally in the frontal/lateral/axial planes of the vertebra
intervertebral rotation	
from T_1-T_2 to L_4-L_5 (°)	frontal/lateral/axial rotations defining the orientation of the vertebra in relation to the preceding vertebra through successive rotations defined locally in the frontal/lateral/axial planes of the vertebra

---

[2] Patient Plane: the patient's personal frontal plane during EOS examination, independently of its relative position to EOS Radio Plane; Radio Plane: main frontal plane perpendicular to EOS AP and parallel to EOS LAT X-ray direction

3.4 Analysis of lower limb EOS 3D reconstruction parameters

In our adult orthopedic lower limb study, mean values of all sterEOS clinical parameters were evaluated within each group of normal, hip and knee arthritic patients and between patient groups, as well.

In our postoperative traumatological lower limb study, corresponding parameters of both limbs were recorded and values of the operated side were compared to the contralateral, intact side which were treated as normal references. Compared parameters included femur length, tibia length, total length, mechanical femoral and tibial angle, femoral torsion, tibial torsion, collodiaphyseal angle, knee valgus/varus and flessum/recurvatum.

3.5 Validation of frontal and sagittal curve data from EOS 3D reconstructions

Validation of frontal and sagittal spinal curve parameter values obtained by EOS 3D reconstructions was performed by comparative analysis to parametric values obtained with manual 2D angle measurements according to the Cobb's method routinely used in clinical practice. Accuracy, reliability and reproducibility of measurement data were verified by statistical methods.

Measurements were performed by three independent examiners with experience in both manual 2D measurements and EOS 3D reconstructions, using biplanar EOS X-ray images of our 201 study subjects. In frontal plane curve measurements, position of upper and lower end vertebrae of curves was agreed upon by examiners in advance. Each manual 2D measurement was performed three times while patient identities were masked from observers, and bias from learning was controlled by random selection of cases for each measurement set. Each EOS 3D reconstruction using the "full 3D" method was carried out two times for each case. Statistical analysis of coronal curve angles, T_4-T_{12} kyphosis and L_1-L_5 lordosis values was performed using a statistical software package SPSS v16.0.

Accuracy of sterEOS 3D measurement sets data compared to 2D manual values was evaluated by means comparison *t* test, and their relationship was tested by Pearson bivariate correlation analysis. Reliability analysis was made by calculating intraclass correlation coefficients (ICCs) for intraobserver reproducibility and interrater reliability, based on the alpha two-way random model with consistency (for intraobserver ICC) or absolute agreement (for interrater ICC).

3.6 Vertebra vector-based 3D visualization of the spine

The concept and method of "vertebra vector" was introduced by our workgroup, for a simplified and abstract visualization of horizontal plane view images of sterEOS 3D reconstructions to facilitate their comprehension and numerical evaluation.

Definition of the vertebra vector

A vertebra vector is, equivalent by definition to a mathematical vector entity, a replacement for a real vertebra while preserving crucial information for its size, position, orientation, and rotation in 3D. A vertebra vector is able to replace its corresponding vertebra both in abstract visual representation and mathematical attributes.

The midpoint of the interpedicular line connecting the pedicles of a vertebral body is the starting point of the vector, designated by convention *point A*. A line drawn from *point A* in parallel to the plane of the upper endplate in sagittal view and along with the symmetry of the vertebral body in horizontal view until terminal *point B* of the vector is created at intersection with the frontal edge of the vertebral body. *Vector AB* thus appears as a line starting at the midpointof the interpedicular line and ends at the intersection with the ventral surface of the vertebral body, forming the symmetry axis of the vertebra body in the horizontal plane view.

Calibrated coordinate system for vector coordinates

By placing a vertebra vector *AB* inside a standard Cartesian 3D *(x, y, z)* coordinate system, calculation of coordinate values X, Y, Z of starting *point A* and terminal *point B* is possible. Axis *x* of the coordinate system is the interacetabular line connecting the two acetabular centers in horizontal plane view images of EOS 3D reconstructions. *Origin* of the coordinate system is the midpoint of the interacetabular line. Axis *y* is an axis perpendicular to axis *x* crossing at the *origin*. Axis *z* is an axis perpendicular to both axis *x* and *y*, respectively, and crossing them at the *origin*. Calibration of the coordinate system is based on the length of the interacetabular line in the horizontal plane view. To create a suitable scale, a value of 100 is assigned to the distance between either acetabular centers and the *origin*. The calibration scale is identical for axes *x*, *y* and *z*.

Calculation of vector parameters

Calculation of vector point coordinates along each three axis in the *x, y, z* coordinate system is a straithforward task. Based on vector coordinates $A(A_x;A_y;A_z)$ and $B(B_x;B_y;B_z)$ of vector points *A* and *B* coordinate values AB(x;y;z) of vector *AB* and vector angles α_F, α_S és α_H measured in the frontal, sagittal and horizontal planes of the coordinate system could be calculated by employing standard vector algebraic methods.

Vector-based spinal curve measurement methods

Vector-based spinal curve measurements are performed identical to conventional curve measurement and very similar to the Cobb's method. Only difference is, that instead of lines corresponding to the upper and lower endplates of end vertebrae of the actual curve, for coronal curves in the frontal plane lines corresponding to the interpedicular lines; for sagittal curves in the sagittal plane lines corresponding to the vectors themselves are used.

Vector elements and vectors were generated for every vertebra in spine 3D reconstructions of all cases by using a supplementary software tool of sterEOS called *Vertebra Vector Tool v3.1,* provided by the manufacturer. Vector coordinates and vector parameter values in all three planes of the coordinate system are calculated by this software tool, furnishing all desired measurement values for vector-based frontal and sagittal spinal curve measurements.

3.7 Validation of vector-based 3D parameters and their use for evaluation of deformity progression and surgical correction

Validation of vector-based 3D parameters

Validation of parameters from vector-based frontal and sagittal spinal curve measurements was also performed by comparative analysis to parametric values obtained with manual 2D angle measurements according to the Cobb's method routinely used in clinical practice, identical to methods outlined in *Chapter 3.5*. Accuracy, reliability and reproducibility of measurement data were verified by statistical methods. Measurements were performed by the same three independent examiners with experience in both manual 2D measurements and EOS 3D reconstructions, using methods identical to the ones used for validation of EOS 3D reconstructions. Data for coronal curve angles, T_4-T_{12} kyphosis and L_1-L_5 lordosis were again evaluated and statistical analysis was performed using a statistical software package

SPSS v16.0. Accuracy of vector-based measurements data compared to 2D manual values was evaluated by means comparison *t* test, and their relationship was tested by Pearson bivariate correlation analysis. Reliability analysis was made by calculating intraclass correlation coefficients (ICCs) for intraobserver reproducibility and interrater reliability, identically to methods described in *Chapter 3.5*.

As a supplementary measurement set, evaluation of sagittal wedging of lumbar L_5 vertebrae visible in EOS LAT X-rays was also measured for all cases, by conventional manual measurement of the angle between lines corresponding to the upper and lower endplates of vertebra L_5. The mean value of this was compared to the value difference of L_1-L_5 lordosis obtained by vector-based 3D and conventional 2D measurements, for all patients together, and in subgroups based on the magnitude of frontal spinal curves.

Vector-based evaluation of spinal deformity progression and the result of surgical correction

For evaluation of spinal deformity progression, comparison of examination data of the same patient at two or more distinct dates was carried out. This included either visual interpretations of EOS 3D reconstruction-based and vector-based visualizations, or parametric assessments of values from sterEOS 3D clinical parameters and vertebra vector parameters.

Analysis of preoperative EOS X-ray images and EOS 3D reconstructions as well as vertebra vectors generated from EOS reconstructions of the 95 patients undergoing surgical correction was done according to the standard spine procedure. For postoperative data, EOS examination 3 days following surgery, EOS 3D reconstruction and vertebra vectors generation were performed identical to preoperative circumstances. Comparison of pre- and postoperative data were also performed by visual and parametric evaluation.

Parameters analysed included coronal curve magnitude measured by a manual 2D method (Cobb), values for T_4-T_{12} kyphosis, L_1-L_5 lordosis, axial rotation (AVR) value of the apical vertebra of the curve (APV) as calculated by sterEOS, change in coronal curve magnitude after surgery (ΔCobb), and horizontal plane vector parameters of the apical vertebra (APV-A_x, APV-B_x, APV-α_H) and their value changes after surgery (ΔAPV-A_x, ΔAPV-B_x és ΔAPV-α_H).

Comparative analysis was performed by means comparison *t* test, relationship between data pairs was evaluated by Pearson bivariate correlation and linear regression analysis, using statistical software package SPSS v16.0.

4. RESULTS

4.1 Application of the EOS 2D/3D system for 3D evaluation of adult lower limb deformities

In our normal group representing a healthy adult population the following measurement values were obtained: femur length was 42.9 cm (range, 37.3–50.8 cm), and tibia length was 37.1 cm (range, 32.6–44.4 cm). The longest tibia belonged to the longest femur. A pairwise comparison of these values revealed that they were directly proportional with minimal deviations. Femoral head diameter was 44.5 mm (range, 38.6–55.3 mm), while the femoral neck length was 50.5 cm (range, 40.9–63.4 cm). Length and diameter values of males were larger than those of females. Neck-shaft angle in males was 129° (116–142°), which was significantly greater than in females 127.8° (range, 114–141.6°). HKS angle was 4.8° (range, 1–8.6°), with 4.6° in females and 4.9° in males.

The angle of the femoro-tibial axis enclosed by the femoral and tibial mechanical angles in the frontal plane was -0.8° (range, -7.5–+5.5°), i.e. a small varus position. In males this parameter was -2.3° (i.e., varus), while in females it was 0.7° (i.e., valgus). Analysis of group individuals based on their varus/valgus values, 125 knees belonged to a subgroup with normal axis position when it did not deviate more than 5° from zero. The remaining three knees was found with a mean -4.0° varus position. Mean value of angle between the mechanical axes of the femur and the tibia in the sagittal plane (flessum/recurvatum) was -1,2° (slight recurvatum). A difference in flessum/recurvatum values based on sex was found to be nearly 5° (females, -3.7°; males, 1.2°) and it could be considered significant.

3D values for torsion were remarkably diverse. The average value of femoral torsion was 17.1° (range, -4.4 to 39.1°) with a standard deviation of 11.51°. Anteversion in females was 19.2°, 4.1° greater than in males. Average tibial torsion was 36° (range, 16.6–52.3°), indicating a significant outwards rotation. The average value in females was higher than in males (37.6° and 34.2°, respectively). The value of femoro-tibial rotation measured by sterEOS is positive when the tibia is rotated outwards and negative when rotated inwards. Total mean value was 2.3° (range, -10.7 to 14.8°), with a standard deviation of 7.16°. Similarly to the other torsion parameters, the mean value in females (3.6°) exceeded the one in males (0.9°).

In our group of 37 hip arthritis patients, the mean neck-shaft angle, femoral antetorsion, femoral and tibial length, as well as the total length of the extremity showed reduced values compared to those in the healthy population. Higher values were found for femoral offset compared to normals.

When our group of 32 knee arthritis patients was analysed, subgroups could be demonstrated based on their lower extremity varus/valgus alignment. Seven knees were found showing normal axis position with an average value of -0.9° (range, -4° to +5°), 35 knees exhibiting varus position with an average of -8.8° (range, -16° to +5°), and four knees with a valgus position with an average of 9.6° (range, 5−20°). Our results demonstrate that the arthritic knee varus position was the most typical knee axis alignment. Its value, however, was much more pronounced compared to the value found in our healthy subgroup with varus alignment (-6.0° versus -0.8°, respectively).

4.2 Application of the EOS 2D/3D system for evaluation of lower limb fractures after osteosynthesis

Results obtained from 60 limbs of 30 patients after osteosynthesis for lower limb fractures were analysed in subgroups according to the localisation of fractures. Due to the inclusion of pelvic anatomical landmarks to the 3D reconstruction process, true 3D values of clinical parameters are calculated relative to the frontal reference plane passing through both acetabular centers ("Patient Plane").

In the subgroup of 10 pertrochanteric fracture cases, femur length, neck length, mechanical femoral angle and femoral torsion were evaluated both in the operated and healthy legs. Values of the two sides were compared to each other. It is important to note, that value differences of the operated leg do not represent absolute deviations, only a relative discrepancy relative to the contralateral leg treated as a normal reference. Significant differences were found for postoperative femur length by 0.8 cm shortening, femoral mechanical axis by 2° and neck-shaft angle by 5.3°. Reduction of the femoral neck length by 0.11 cm and a difference in femoral torsion by 1.1° was statistically not significant.

In the subgroup of 8 femur diaphysis fracture cases, femur length, mechanical femoral angle and femoral torsion were evaluated both in the operated and healthy legs. A significant reduction of femur length by 1.1 cm, a significant difference of mechanical angle and femoral torsion by 0.8°and 7.2°, respectively, were documented.

In the subgroup of 12 tibia diaphysis fracture cases, tibia length, tibia mechanical angle and tibial torsion were evaluated both in the operated and healthy legs. There was a significant and more pronounced difference of the length and mechanical angle values compared to femoral fractures. Mean shortening of tibia length was 1.7 cm, 2.1° angle difference to varus position and 3.1° torsional difference with internal rotation.

4.3 Application of the EOS 2D/3D system for pre- and postoperative evaluation of spinal deformities

Although only a relatively small sample of 201 patients was included in studies presented in this dissertation with respect to the number of cases examined between 2007 and 2012, examinations with the EOS 2D/3D system became a standard routine procedure at our Department. Of the total 7100 EOS biplanar X-ray exams within this 5-year time frame, 2900 was indicated for spinal deformity (mostly adolescent idiopathic scoliosis and secondary scoliosis related to various system diseases in children), or for spine-related complaints (i.e., degenerative spinal conditions in elderly adults). Postoperative EOS examinations of 450 patients who underwent spine correction surgery was also included in this number. This means that – aside from a few occasions due to temporary technical breakdowns – in case of *practically all* spine patients presented to our Outpatient Clinic or operated with correction surgery, radiological assessment of the spine has *always* been performed by the EOS 2D/3D system.

During this 5-year period, the number of full-spine EOS 3D reconstructions based on biplanar EOS X-ray examinations reached 2700, shared in a 40-30-15-15 ratio by four physicians of our Department as sterEOS operators. Of the total 2700, 150 was postoperative EOS 3D reconstructions for patients after surgical correction.

4.4 Evaluation and validation of EOS reconstructions for 3D characterization of spinal deformities

Validation of EOS 3D reconstruction parameters for evaluation of frontal and sagittal curves

Intraobserver reproducibility of frontal and sagittal curve measurements based on conventional methods (manual 2D) and EOS 3D reconstructions (sterEOS 3D), performed by three independent examiners, were analysed by evaluating intraobserver ICC values. Excellent reproducibility was found for each examiners, both for manual 2D and sterEOS 3D measurement values. Peformance of Examiner no 1 showed the overall best results with ICC values between 0.999 and 1.000.

Accuracy and correlation analysis results of curve measurements by sterEOS 3D compared with manual 2D methods were presented to exhibit only statistically non-significant minute differences in coronal curve and T_4-T_{12} kyphosis values (1.22° $p<0.05$ and 0.57° p not significant, respectively) and a statistically significant but small difference (2.0° $p<0.01$) for L_1-L_5 lordosis values. Statistically significant strong correlations were shown to exist between all corresponding pairs of measured parameters.

Interrater reliability of curve measurements for all patients as computed by interrater ICCs demonstrated an overall good reliability of manual 2D measurements (0.971, 0.884, and 0.845 values for coronal curves, T_4-T_{12} kyphosis, and L_1-L_5 lordosis, respectively), that was excelled by significantly higher values for sterEOS 3D measurements (0.985, 0.975, and 0.930 values for coronal curves, T_4-T_{12} kyphosis, and L_1-L_5 lordosis, respectively). The difference between the two methods was very significant for sagittal curve measurements.

Results of accuracy and correlation of curve measurements within the five patient subgroups based on the magnitude of frontal spinal curves could be summarized as differences compared with manual 2D values were found to be small and non-significant, except for sagittal curve parameters in subgroup 4 patients with 3.28° for T_4-T_{12} kyphosis and 4.57° for L_1-L_5 lordosis. Pearson correlation was medium to strong with the exception for subgroup 1 coronal curve parameters (r=0.107).

Interrater ICC values for sterEOS 3D measurements were found to be consistently higher than those for manual 2D in every patient subgroup. Very good-to-excellent values were all close to or more than 0.9 and did not seem to significantly decline with the increase of scoliotic curve magnitude, as demonstrated with manual 2D measurements.

Evaluation of horizontal plane view images of the EOS 3D reconstruction

An opportunity to analyse horizontal plane views of the normal spine was provided by a screening test of young healthy athletes with normal spinal geometry.

Vertebrae of the thoracic and lumbar spine are positioned centrally along the symmetry axis perpendicular to the coronal interacetabular axis of the pelvis – also known as the sagittal median line – with no lateral deviations and almost no axial rotation above detection threshold. Vertebrae positioned along the sagittal median line span a range a bit shorter than, and orthogonal to, the interacetabular distance. This "sagittal span" equals to the maximal space between contour edges of the most ventrally and dorsally positioned vertebra, in horizontal projection to the sagittal median. This observation actually correlates with the typical S-shape of the sagittal spinal curves. Due to their composite 3D projection, distinguishing vertebral bodies and vertebral processes from each other is difficult or not possible.

Analysis of horizontal plane view images of an EOS 3D reconstructed, representative case of the most common type of adolescent idiopathic scoliosis with a single right convex major thoracic curve (Lenke type 1) revealed a few essential differences to observations with normal spinal geometry. Lateral vertebral deviation, well known from AP X-ray visualizations, is the most conspicuous feature. Due to this, the apical vertebra of the curve is seen the most laterally positioned; in a severe right convex major curve, its lateral deviation could reach the outermost contour of the ipsilateral acetabulum.

The next typical difference is that, in contrast to the normal spinal configuration, vertebrae of the thoracic and lumbar spine are positioned alongside and parallel to the interacetabular axis of the pelvis, practically perpendicular to the normal arrangement. In a close relationship with this, "sagittal span" projected to the sagittal median is significantly smaller than in normals, generally less than half of the interacetabular distance. This is the actual horizontal plane representation of the well-known and typical flattening of the sagittal spine due to reduction of thoracic kyphosis and lumbar lordosis.

Axial vertebral rotation, a third characteristic feature of scoliotic deformities, is also clearly visible. Its maximal value corresponds to the apical vertebra of the curve and is usually easily detectable based on positions of spinous and transverse processes of vertebrae, in spite of the composite 3D projection.

Horizontal plane view images of an EOS 3D reconstructed, representative case of the second most common type of adolescent idiopathic scoliosis with a double major curve (Lenke type 3) very well demonstrated lateral deviations of the spine, in opposite directions, according to the right convex thoracic and left convex lumbar curve.

Although less profoundly than in case of the Lenke type 1 deformity above, repositioning of the whole spine alongside and parallel to the interacetabular axis is also visible, as well as a small-degree reduction of "sagittal span" projected to the sagittal median. Opposite directional, axial rotations of vertebrae of the two major curves are quite clearly depicted, as well.

Analysis of horizontal plane view images of an EOS 3D reconstructed, representative case of elderly degenerative scoliosis with a severe lumbar deformity provided a totally different depiction compared to the former two, typical adolescent spine deformities. Positioning of the thoracic region vertebrae below (in reality, ventrally of) the interacetabular axis is the most pronounced spinal deviation and the "spread out" configuration of the upper and middle section of thoracic vertebrae causes a marked increase of the "sagittal span" projected to the sagittal median. Lateral deviation of the lumbar region is also clearly visible while apical vertebra of the curve appears in a dorsal position to the remaining vertebrae of the curve, with a substantial degree of axial rotation.

4.5 Analysis and validation of vector-based visualization of EOS reconstructions for 3D characterization of spinal deformities

Vertebra vector-based horizontal plane view visualization of the normal spine appears to be simpler and more comprehensible than its EOS 3D reconstruction-based counterpart described in *Chapter 4.4*. Vertebrae positioned along the sagittal median line are depicted as lining up on axis *y* of the coordinate system, with minimal lateral deviations (any $B_x < \pm 5$ units), and axial rotation represented by the horizontal vector angle is negligible ($\alpha_H < 3°$). Due to a slightly increased thoracic kyphosis within normal limits of the analysed case, "sagittal span" of vectors (similarly defined as for vertebrae, only using the vectors themselves instead of vertebral contour lines) is about 140 units, i.e., 1.4-times the half of the interacetabular distance, and most of the vectors appear above axis *x*. Similar to 3D reconstructed vertebrae, vectors are projected on each other, therefore their exact spatial position and spatial configuration of the spine represented by them is difficult to conceive.

Vector-based horizontal plane view visualization of a representative scoliosis case with a single right convex major thoracic curve shows gradually increased lateral vector deviations into the negative range of axis *x*, reaching a maximal value with apical T_9 vector terminal point beyond the acetabular center (B_x=-110.3). Transversal repositioning of vectors parallel to the interacetabular axis x is prominent. "Sagittal span" of vectors projected to axis *y* is less than 75 units. Gradually increased axial rotation of vectors in the curve is indicated by rotated position of vectors T_6-L_2 with a maximal value shown by apical T_9 vector(α_H=31.1°).

Vector-based horizontal plane view visualization of a representative scoliosis case with a double major curve reveals a marked S-shaped rearrangement of vectors, corresponding to the double major curve. Maximal values for lateral deviation and axial rotation of the vectors are found for L_2 apical vector of the lumbar major curve (B_x=63.3; α_H=17.2°). "Sagittal span" of vectors projected to axis *y* is 125 units.

Vector-based horizontal plane view visualization of a representative case of elderly degenerative scoliosis with a severe lumbar deformity, similar to cases described above, provided a more obvious and more accurate depiction about the type and severity of the deformity. Vectors of the thoracic region are "spread out" due to the profound sagittal imbalance caused by the bent-forward posture of upper body. Maximal values for lateral deviation and axial rotation is shown for apical vector L_1 of the lumbar curve (B_x=91.0, α_H=33.5°). Visual configuration of the lumbar spine region is aberrant due to the paradox lumbar kyphosis present. "Sagittal span" of vectors projected to axis *y* is more than 210 units, i.e. longer than the interacetabular distance.

Validation of vertebra vector-based parameters for frontal and sagittal spinal curve measurements

Intraobserver reproducibility of frontal and sagittal curve measurements based on conventional methods (manual 2D) and curve measurement methods by vertebra vectors generated from EOS 3D reconstructions (VV 3D), performed by three independent examiners, were analysed by evaluating intraobserver ICC values of individual measurement sets of each examiners. ICC values for both manual 2D and VV 3D measurements demonstrated excellent reproducibilty, for all three examiners.

Accuracy and correlation analysis results of curve measurements by VV 3D compared with manual 2D methods were first evaluated for all 201 patients together in the validation study. The vector-based measurement methods produced only statistically non-significant minute differences in coronal curve and T_4-T_{12} kyphosis values (-0.02° and 0.57°), but a statistically significant, smaller value for L_1-L_5 lordosis by 9.03°. Relationship between measurement values by the two methods was found to be statistically significant and strongly correlated.

Interrater reliability of curve measurements for all 201 patients was computed by interrater ICCs. Reliability of manual 2D measurements were good-to-excellent (ICC values of 0.971, 0.844, and 0.845 for coronal curves, thoracic kyphosis, and lumbar lordosis, respectively) but were surpassed by significantly higher ICC values of vertebra vector–based measurements (0.991, 0.982, and 0.971, respectively).

Results of accuracy and correlation of curve measurements were evaluated within 5 patient subgroups based on the magnitude of their coronal curves. Differences compared with corresponding manual 2D values were found to be small and nonsignificant, except for lordosis parameters in all patient groups.

Pearson correlations between corresponding measurements were medium to strong and statistically significant, except for coronal curve parameters in subgroup 1 (r=-0.055, *p* non-significant) and lordosis parameters in subgroup 5 (r=0.305, *p* non-significant).

Interrater reliability analysis of curve measurement within patient subgroups was also performed. Interrater ICC values for vertebra vector–based measurements were found to be excellent, ranging from 0.994 to 0.915 for coronal curves, from 0.987 to 0.978 for kyphosis, and from 0.985 to 0.961 for lordosis, in patient subgroups 1 to 5. These values were consistently higher than those for manual 2D in every patient group, and unlike their 2D manual counterparts, their values did not seem to significantly change with the increase of scoliotic curve magnitude.

To clarify the reason for getting statistically significant smaller values for lumbar lordosis by the vector-based measurement method in all 201 patients (by 9.03°) and within patient subgroups (in range of 5.69°−10.98°), relationship between L_5 wedge angles and differences in lumbar lordosis measurement values. It was shown that only small and statistically non-significant disparities exist, either for all patients as a whole or within patient subgroups 1−5, i.e., there might be a strong relationship between these two things, or in other words, the magnitude of consistently lower lordosis values may be equal to the L_5 wedge angle sizes.

Application of vertebra vectors for evaluation of deformity progression and results of surgical correction

Evaluation of deformity progression was documented by a vector-based visual analysis and parametric values of a representative adolescent idiopathic scoliosis case with a single left convex major thoracic curve, showing a severe and rapid progression (with only 9 monts between the two EOS examinations). As a result of progression, an increasing lateral deviation and horizontal plane vector angle of apical vector (APV) T_9 was very apparent in vector-based horizontal plane view images.

Vector-based parametric evaluation of this case demonstrated changes of coronal curve values from 62.2° to 88.0° *(41.5% worsening),* apical vector axial rotation (T_9 APV-α_H) values from 17.8° to 31.4° *(76.4% elevation),* and lateral-most deviation of apical vector terminal point B (T_9 APV-B_x) values from 83.1 to 170.1 (*104.7% increment,* the most marked change among all vector parameters).

Evaluation of results of surgical correction was demonstrated by a vector-based visual analysis and parametric values of a representative scoliosis case with a double major curve (Lenke type 3) based on preoperative and postoperative EOS examinations. The most pronounced changes are revealed by horizontal plane view images. Due to surgical correction, the initial lateral deviation of vertebra vectors disappeared, and they line up along axis *y* while their axial rotation was significantly decreased.

According to vector-based parametric data, values for thoracic and lumbar coronal curves changed from 47.0° and 53.7, respectively to 10.2° and 2.4°, respectively. Changes in parameter values of apical vectors T_8 and L_2: T_8 APV-α_H 7.9°–6.3°; T_8 APV-B_x 1.2–1.7; L_2 APV-α_H 21.9°–4.3°; L_2 APV-B_x 68.3–9.0.

Comparative analysis of the result of surgical correction based on parameters measured by vector-based methods was also performed for the group of 95 patients among the original 201 cases who underwent spinal correction. Results of the validation study for unoperated (i.e., preoperative) patients detailed earlier were also confirmed for postoperative data: value-difference between measurements by conventional 2D and vector-based 3D methods was negligible for Cobb angle of coronal curves (0.21°), small for thoracic kyphosis (2.04°), with statistically significant and strong correlations (r=0.935 and r=0.896). Difference in values for L_1-L_5 lordosis measured by the two different methods was again significant (-7.04°), with strong correlation (r=0.968), and appeared to be closely linked to L_5 vertebral wedging, as demonstrated for unoperated cases. Values of apical axial vertebral rotation of the coronal curves, this time measured with sterEOS-based and vector-based methods, showed only a tiny difference (0.16°) but strong corrrelation (r=0.968).

Correlation analysis between preoperative/postoperative coronal curve Cobb's values and horizontal plane vector parameter values showed the strongest relationship for apical vector terminal point B (APV-B_x), representing the lateral deviation of the apical vertebra, with correlation coefficients r=0.701 (preop) and r=0.434 (postop). Correlation between changes after correction in parametric values of coronal curve (ΔCobb) and horizontal plane vector parameters again revealed the strongest correlation (r=0.480) with change in value for coordinate X of apical vector terminal point B (ΔAPV-B_x).

In further comparative analysis by linear regression of *preoperative* values of apical vector parameters and *preoperative* Cobb's angle, an important additional detail was revealed with respect to our understanding of the relationship between horizontal plane vector parameters and coronal curve magnitude. Strongest relationship was shown between the Cobb's angle value and, again, value for the coordinate X of apical vector terminal point B, indicated by the highest regression coefficient (R^2=0.459). The relationship with the axial rotation represented by the horizontal plane vector angle of apical vector (APV-α_H) was significantly weaker (R^2=0.202).

5. DISCUSSION

5.1 Application of the EOS 2D/3D system for 3D evaluation of adult lower limb deformities

There are a limited number of international and national publications related to the normal geometric parameter values of the lower limbs. Likewise, only a very few publications were available with regards to the application of the EOS 2D/3D system in lower limb examination until our study has been completed and published. Since no publication was known from others concerning normal values for lower limbs obtained by the EOS 2D/3D system, results of our study was compared with results obtained by other methods.

Values for neck-shaft angle, femoral antetorsion, the femoral and tibial length, as well as the total length of the extremity in our healthy group are in good agreement with normal values presented in the literature. The mean value of neck-shaft angle for the healthy population was identical to the value of 128.23° reported by others. Our results for femoral antetorsion are also comparable to those described by others.

Comparing results for our healthy knee group with those presented by others, it is concluded that our value of femorotibial angle of -0.8° varus is in very good agreement with the value of 0° reported.

Compared to our healthy subjects, a decreased mean neck-shaft angle value was found in our patients with hip arthritis. Considering that the average age of our healthy group was 26.3 years (range, 19–39), whereas it was 67 years (range, 53–80) in our arthritic group, it can be concluded that aging may have an influence on the reduction of neck-shaft angle. This observation seems to be supported by other published reports documenting the neck-shaft angle value to gradually decrease with age.

Femoral antetorsion in our hip arthritic group was found to be 2.7° smaller than in our healthy group, which value still falls within the normal range and corresponds to normal values described by other authors. The decrease in values for femoral offset and total length of lower extremity presented in our study correspond to results reported by others. Comparing our arthritic and healthy groups, an average 1.5-mm difference was found in values of femoral head diameter, a discrepancy which may be caused by osteophytes deposited on the femoral head. No significant difference was found in femoral neck length between our two patient groups, indicating that hip arthritis has no influence on its value.

In our group with knee arthritis 35 knees were shown in varus position and four in valgus position. This corresponds well to observations by others, i.e., varus position was demonstrated to be more common than valgus for knee alignment. Knee degeneration is usually accompanied by axis deviation, although a prevalent role in this is played by alteration of the tibial mechanical angle. In our study the tibial mechanical angle in our knee arthritis group showed a significant difference compared to normal values within our healthy study group (85° in the varus subgroup and 94° in the valgus subgroup), and a similar difference to normal values was reported by other authors, as well.

The EOS 2D/3D system and related sterEOS 3D reconstruction has been shown by our study to be **very suitable for the examination of lower limbs in adults**. With contrast to conventional radiological examinations, high quality biplanar digital X-ray images could be aquired faster, with more efficiency and at significantly lower radiation doses. Relevant **biomechanical and geometrical parameter values of the femur, tibia and the whole lower limb have been first defined by our workgroup worldwide with EOS 3D reconstruction**, for normal healthy adults and patients with hip and knee arthritis.

5.2 Application of the EOS 2D/3D system for evaluation of lower limb fractures after osteosynthesis

To this day, a conventional two-directional X-ray examination is used for the assessment of results following osteosynthesis of long bone fractures of lower extremities. Based on conventional radiography, however, only length and axis of the operated bones could be measured. Loaded long-film or stiched X-rays are required for measurements of the total length of the limb and its mechanical angle relative to the trunk. Nevertheless, rotational values still cannot be evaluated on these X-ray images. In this study application of the EOS 2D/3D system was evaluated for the assessment of results of lower limb fractures, utilizing benefits from radiological characteristics of this new system and advantages of EOS 3D reconstructions.

Average femur length reduction, mechanical axis deviation and torsional difference demonstrated for the group of ten patients with femur pertrochanteric fracture were non-significant. Change of neck-shaft angle by 5° to varus position, and shortening of the femur neck by 0.11 cm, however, are substantial differences that could be attributable to the fracture nature or possible reposition errors.

The minimal femur length reduction and mechanical axis deviation, as well as the torsional difference less than 10° found in our group of eight patients with femur diaphysis fractures demonstrated excellent results of osteosynthesis from a biomechanical viewpoint. This is even more so in comparison with published data, because others reported torsional differences bigger than 15° in 28% of operated cases, and leg shortening bigger than 1 cm with 25% frequency.

In our group of 12 patients with tibia diaphysis fractures, larger differences were found for length and mechanical axis values compared to the groups of femur fractures. These differences could obviously attributable to repositional inaccuracies, although the largest torsional difference or axis deviation was no bigger than 10° and 5°, respectively. Torsional differences reported by others are significantly larger with an average 6.7° in 16.4% frequency.

An increasing number of publications was available from 2010 concerning EOS imaging and 3D reconstruction for lower limb applications, but **to this date no reports has been published regarding the use of the EOS system after osteosynthesis of lower limb fractures. In this respect, our study has a pioneering importance**.

In summary, the **EOS 2D/3D system has been shown** by our study to be **suitable for radiological examinations after osteosynthesis of lower limb fractures**. In contrast with conventional radiography and CT, **length, axis and torsional parameters of the operated and healthy legs could be evaluated and compared with a significantly lower radiation dose**. We are convinced that in spite of a statistically low evidential proof derived from results our relatively small study sample, **this method**, especially for its novelty, **is applicable for accurate evaluation of various posttraumatic defomities**.

5.3 Application of the EOS 2D/3D system for pre- and postoperative evaluation of spinal deformities

By having the very first EOS 2D/3D system worlwide at our University has created the basis for making a significant progress in activities of our Departmental Unit for spinal disorders, and to transfer all the main advantages of EOS examination and 3D reconstruction into our routine clinical practice.

The *first advantage* was **a significantly lowered ionizing radiation dose towards patients** related to EOS 2D/3D full-spine and full-body X-ray examinations. This had its outmost importance with respect to young persons, mostly female, with idiopathic adolescent scoliosis, constituting the largest fraction of our examined spine patient population. Considering the volume of approximately 2900 EOS examinations for adolescent and adult scoliosis during the 5-year period of 2007-2012, and assuming a 50% reduction of harmful radiation dose compared to DR radiography, it was asserted that negative effects from clinically justifiable examinations have been significantly reduced, **satisfying ALARA principles in everyday practice**.

The *second advantage* of the EOS 2D/3D system was that based on biplanar X-ray images simultaneously captured within 10-25 seconds, **without further examinations bearing extra radiation dose to patients, realistic, accurate EOS 3D reconstructions** with relevant orthopedic information of visual and parametric data could be produced, even after surgical correction. We are convinced that, with respect to the large volume of full-spine EOS 3D reconstructions performed during this period, this important advantage has been substantially utilized. This resulted a database of 3D reconstructed spines with an outstanding number of cases even by international comparison, and yielded publication of a review article in English, frequently cited by others as a reference *(Illés T, Somoskeöy Sz., Int Orthop (SICOT) 2012; 36(7):1325-1331)*.

The *third advantage* of the EOS 2D/3D system was the **ability to visualize and evaluate spinal deformities in horizontal plane view** by topview images of EOS 3D reconstructions. Beyond obvious importance of the large volume of completed 3D reconstructions, this new feature had the most pronounced influence on our daily work. This feature has been considered so significant that it was discussed in detail in my dissertation and yielded another published article also frequently cited by others *(Illés T, Tunyogi-Csapó M, Somoskeöy S., Eur Spine J 2011; 20(1): 135-143)*.

In conclusion, our original objective is thought to be fulfilled by our **successful introduction and effective application of the EOS 2D/3D procedure in routine diagnostics of spinal deformities**, and making full use of its advantages. This granted a considerable international reputation to our workgroup. An agreement of official collaboration for research and development has been reached with the manufacturer of the system, that contributed to the successful completion of work presented in the dissertation.

5.4 Evaluation and validation of EOS reconstructions for 3D characterization of spinal deformities

Validation of EOS 3D reconstruction parameters for evaluation of frontal and sagittal curves

Only a few international publications with clinical relevancy related to the new EOS 2D/3D system and its sterEOS 3D reconstruction could been found during our studies. Moreover, most of these published papers usually provided information about studies performed either with early prototypes, on small patient samples or under experimental settings.

Conventional spinal curve measurement methods are all based on the original or modified versions of manual angle measurements in AP and LAT X-rays described by Cobb in 1948. Its wide acceptance and application in clinical practice is mainly due to its simplicity and convenience, despite an ongoing debate about its problems with accuracy and reproducibility.

A fundamental argument against measurements and evaluation of spinal deformities based on these methods stems from their questionable ability for an accurate and full representation of complex 3D entities like vertebrae and scoliotic deviations, based on projections in 2D planes of X-ray images.

With respect to all the above, a controlled, non-randomized, retrospective clinical validation study of spinal curve measurements data based on our routinely used EOS 3D reconstructions against data obtained by conventional 2D methods seemed to be warranted, on a medium-sized sample of patients with normal spines or with spinal deformities of mixed composition. Measurement data sets of frontal and sagittal curves proved that results of this new method have excellent reproducibility and reliability while being highly accurate with negligible, smaller than 2° differences compared to conventional measurements data and a statistically significant strong correlation was found between respective data pairs. Accuracy and reliability of measurements was found to be independent from the magnitude of coronal curves, a problem well known for conventional manual 2D methods.

Intraobserver reproducibility of our three examiners was excellent for either manual 2D or sterEOS 3D measurements. This gave a solid basis for the implementation of our next objective, evaluation of interrater reliability of measurements methods. Interrater reliability of conventional 2D measurements was good and excellent and showed a good agreement with data published by others. Interrater reliability of measurements based on EOS 3D reconstructions surpassed these with ICC values 0.985, 0.975 and 0.930 for coronal curves, T_4-T_{12} kyphosis and L_1-L_5 lordosis, respectively.

These results confirmed that **sterEOS 3D curve measurement methods based on EOS 3D reconstructions may completely substitute for respective conventional 2D methods**.

Results of patient subgroups with increasing magnitude of coronal curves proved that **accuracy of sterEOS 3D-based measurements was not adversely affected by the inceasing value of Cobb's angle or sagittal imbalance.** Interrater reliability in patient subgroups was consistently higher – with good and excellent values – for sterEOS 3D-based measurements than for respective manual 2D measurements. This contrast was especially profound in case of sagittal curve measurements in a patient subgroup with severe coronal deformities of Cobb's angle above 50°.

Results of our validation study could be summarized as spinal curve measurement data based on this new method **provide more accurate, more reproducible and more reliable results than conventional 2D methods**, irrespective of the seriousness of clinical cases. Suitability and valuability of the clinical procedure based on EOS 3D reconstructions in examination and evaluation of spinal deformities was proven, and **our documented results had a major international significance**.

Evaluation of horizontal plane view images of the EOS 3D reconstruction

With respect to being among the very first worlwide at introducing the EOS 2D/3D procedure to routine clinical activity, **our workgroup has been first to lay down principles for evaluation of horizontal plane view images** of EOS 3D reconstructions, that eventually lead us to the introduction of a new concept of vertebra vector-based visualization and evaluation.

Topview images of EOS 3D recontructions allow for simultaneous overview of vertebrae from the upper thoracic through the lumbar region until the pelvis, beneath each other in 3D. They convey relevant visual information about position, rotation of individual vertebrae, as well as relative relationship to other vertabae and the pelvis. Apical vertebrae of the curves could be highlighted alone, for a clear assessment of their axial rotation and position relative to the pelvis. Evaluation of relative 3D positions of the spine and pelvis provides indirect information about the coronal and sagittal balance.

Repeated and consistent analysis of scoliosis cases of different curve types resulted the identification of typical configurations and characteristics, appearing in horizontal plane view images, that are not as nearly obvious in the other two main plane views or specifically unique due to specificities of the horizontal plane view.

Detailed analysis was performed in four basic configuration types of EOS 3D reconstructions: normal spines of healthy athletes, idiopathic scoliosis cases with a single major thoracic (Lenke type 1) or double major thoracolumbar/lumbar curves (Lenke type 3), and elderly degenerative scoliosis cases with lumbar deformities.

In horizontal plane topview images of the normal spine vertebrae appear postioned in the sagittal median of the body, perpendicular to a virtual interacetabular axis connecting the two acetabular centers. No lateral deviation is detectable, axial vertebral rotation, indicated with great sensitivity by spinous and transverse processes of vertebrae, is negligible.

Three characteristic features were detected by analysis of Lenke type 1 cases in horizontal plane topview images of EOS 3D reconstructions. The first, lateral deviation of the spine – the main deviation of scoliosis obvious in AP X-rays –, appears in topview images of the sterEOS 3D model as deviation to the convex side of the curve with the apical vertebra in the outermost position. The second characteristic feature is that the thoracic and lumbar region is positioned almost parallel – instead of being perpendicular – to the interacetabular axis, and the ventro-dorsal distance projected to the sagittal median axis ("sagittal span") is reduced. This is the actual horizontal plane representation of the flattening of thoracic kyphosis and lumbar lordosis described in LAT X-rays. The third characteristic feature, linked to the nature of scoliotic deformities, a series of axial vertebral rotations is clearly visible with maximal value for the apical vertebra. This means that all three characterictic deviations described in separate planes are visualized in a single plane view.

Horizontal plane topview images of Lenke type 3 deformities revealed the same, although less marked, characteristic features described for Lenke type 1 cases, evidently for the pair of major curves.

Horizontal plane topview visualization of elderly degenerative scoliosis also provided insights to three-dimensional deviations in all three main planes. Lateral deviation of the lumbar region appears as a lateral vertebral repositioning along the intraacetabular axis and orthogonal to the sagittal median axis, just as in the former two cases.The most conspicuous feature is the repositioning of vertebrae of the thoracic region below (in reality, ventrally of) the interacetabular axis and the "spread out" configuration of the upper and middle thoracic region, with markedly increased "sagittal span" of the spine due to a large ventro-dorsal distance projected to the sagittal median axis. This is indicative for big changes in sagittal curves, with a diminished lumbar lordosis and a severely increased thoracic kyphosis, as well as for the bent-forward posture of upper body. Apical vertebra of the lumbar curve also clearly depicted in a most dorsal position compared to other vertebrae with a high degree of axial rotation. This specific scoliotic case represents a special type of lumbar scoliosis called hyperrotatory paradox kyphosis with a kyphotic deviation and maximal axial rotation of the lumbar apical vertebra.

With the knowledge of horizontal plane topview visualizations of the normal spine, visual representation of principles for an ideally performed surgical correction becomes obvious. The goal is to perfectly restore the normal status. Based on postoperative horizontal plane topview images, the triple goal of an optimal correction: (1) elimination or reduction of lateral deviation; (2) repositioning of vertebrae along the sagittal median axis and increase of the "sagittal span" to a 50-75% value of the interacetabular distance; and (3) elimination or reduction of axial vertebral rotation. Horizontal plane topview images provide insights and make possible evaluation of these three principles at the same time.

In conclusion, **horizontal plane topview images** of EOS 3D reconstructions bring a unique possibility for visualization of spinal deformities: **components of scoliotic deviations present in all three planes are depicted.** Semi-quantitative evaluation of these deviations is possible based on their position relative to the sagittal median axis, pelvis, acetabula and interacetabular axis and distance. **Topview 3D images provide an excellent insight into all specific aspects of deviation in frontal, sagittal and horizontal planes**, thereby offering an unmatched solution compared to other recent clinical options.

5.5 Analysis and validation of vector-based visualization of EOS reconstructions for 3D characterization of spinal deformities

In idiopathic scoliosis, either the origin and nature of the structural deformity or the course of progression is unknown. The first step is believed to be related to vertebral rotation, which causes sagittal plane instability and a modest frontal plane imbalance. After the initial onset, deformations progress with a self-supporting biomechanical process during periods of fast growth in childhood and adolescence. Various methods have been developed for assessment of axial vertebral rotation but their reliability has been shown very limited because 2D X-ray images provide inadequate quantitative or qualitative information on anatomical landmarks needed to evaluate axial rotation. Significant progress was made with axial rotation measurements based on 3D reconstructions from digitized biplanar X-ray images. The most accurate measurement of vertebral axial rotation has been achieved in axial CT images. The use of CT in routine scoliosis diagnosis, however, is limited due to its high radiation dose and the supine position during imaging. Another problem is related to the level of rotation measurement within the vertebral body, since the value for rotation can vary significantly, due to vertebral torsion, when measured at the lower and upper endplates of the same vertebra.

A vertebra vector, by its definition, **eliminates variances in axial rotation values due to vertebral body torsion**, since the relative distance of the vector from the upper endplate is constant for each vertebra. A vertebra vector **furnishes complete and accurate information concerning the size, position, orientationand rotation of its respective vertebra in all three planes.**

In horizontal plane images of EOS 3D reconstructions, after using the interacetabular distance between acetabular centers as a calibration scale and creating a standard cartesian 3D coordinate system, vector parameter values placed in this uniformly and individually calibrated coordinate system is possible.

Spinal deviations could be quantified based on vector parameters in all three planes, thus in horizontal plane topview, as well. Similar to conventional curve measurement methods, **magnitude of frontal and sagittal curves could be evaluated, axial rotation of the vector substituting for the vertebra could be calculated.**

In summary, horizontal plane topview images of vector-based visualizations convey simpler and more intelligible visual information than similar images of EOS 3D reconstructions, while all advantages of the latter is preserved and augmented. Negligible deviations or ones undetectable by other methods – i.e., minimal axial vertebral rotation – could be also identified with high sensitivity. Due to easily quantifiable vector parameters placed inside a 3D coordinate system using an individual scale based on patient-specific geometry, **evaluation and comparison of spinal deformities could be objectively performed with high accuracy.**

Validation of vertebra vector-based parameters for frontal and sagittal spinal curve measurements

Accuracy of vector-based curve measurements for frontal and thoracic kyphosis was excellent with minimal differences. For the **discrepancy of 9.03° in lumbar lordosis** values, the **difference was shown to closely linked to L_5 vertebral wedging of individuals studied.** Identical results were found when analyzed for all individuals in our patient sample or in patient subgroups based on the size of their coronal curves. An explanation for this apparent error is, that a conventional lordosis measurement calculates the angle between the upper endplate of L_1 and *lower* endplate of L_5, but the vector-based measurement uses L_5 vector parallel to the *upper* endplate of L_5. Therefore, even the smallest angulation between endplates of L_5 would result in a conventional lordosis value increased by the respective size of L_5 wedge compared to the vector-based lordosis value. Due to that, a **further advantage of the vector-based curve measurement, that it excludes an inherent error of the conventional L_1-L_5 lordosis measurement** caused by L_5 vertebral wedging.

Excellent results were shown for reproducibilty and reliability of all vector-based measurements (range of intraobserver ICC values 0.996-1.000, and iterrater ICC values of 0.991, 0.982 and 0.971). These values were significantly higher than ones for conventional measurements (range of intraobserver ICC values 0.994-1.000, and iterrater ICC values of 0.971, 0.844 and 0.845).

Reliability analysis of vector-based measurements within patient subgroups based on the size of their coronal curves has shown **excellent interrater ICC values in all five subgroups**, with 0.994-0.915 values for frontal curves, 0.987-0.978 for thoracic kyphosis, and 0.985-0.961 for lumbar lordosis. These were consistently higher than values for manual 2D measurements, and **did not show a diminishing tendency with increasing magnitude of coronal curves.**

According to these findings, vertebra vector–based curve measurements are able to **fully substitute for conventional coronal and sagittal curve measurements**, with **similar accuracy and higher reliability.**

Application of vertebra vectors for evaluation of deformity progression and results of surgical correction

Evaluation of 5 patients with a definitive progression in the study group was made significantly more clear and easier by vector-based visualization and quantitatively more exact by vector parameter values. In a representative case with a fast progressing Lenke type 1 left convex curve, vector-based parametric data indicated that while the change was "only" from 62.2°to 88.0° for the coronal curve value (a 41.5% increase) and from 17.8° to 31.4° for apical vertebral rotation (a 76.4% increase), the value for lateral deviation of the apical vertebra vector was dramatically increased from 83.1 to 170.1 (a 107.4% change, the most pronounced among vector parameters). According to these findings, **vector parameter value B_x** representing lateral deviation of the apical vertebra of the curve **seems to be the best indicator for deformity progression**, because it shows deformity change more sensitively and efficiently than any other parameter conventionally used as progression indicators (i.e., the Cobb's value).

Analysis of 190 EOS 3D reconstruction cases based on pre- and postoperative EOS examinations of 95 patients operated for spine correction, as well as evaluation of vector-based 3D visualizations and parametric data of the same cases **has proven suitability of the vector-based method for 3D visualization and exact parametric evaluation of surgical correction results.**

Ideal correction was convincingly illustrated by vector-based horizontal plane topview images before and after surgery with resulting repositioning of vectors representing vertebrae of the curve along the sagittal median axis perpendicular to the interacetabular axis, with minimal degree of lateral deviation and axial rotation. Successful reconstitition of sagittal curves was indicated by an increased value of "sagittal span" as projected to the sagittal median axis, equal to or more than half of the value of interacetabular distance.

In order to make visual analysis more exact, in comparison tests based on vector parameters, a minimal discrepancy and strong correlation was confirmed between values of sterEOS 3D and vector parameters, eventually proving the **suitability of the vector-based method for evaluation of surgical correction.**

By analysing value changes of pre- and postoperative coronal curves measured by vector-based methods with relation to value changes of other vector parameters, a few interesting observations were made. In contrast with our expectations, only a **weak correlation and low linear regression was found between preoperative Cobb's angle and apical vertebral rotation**, indicating that besides a suggested critical effect of axial rotation, other factors may also play a significant role in the complex mechanism of the onset and progression of spinal deviations. This view may be supported by our finding that a **significantly stronger correlation and higher linear regression was found between** values of **preoperative Cobb's angle and vector parameters indicating apical vertebral lateral deviation** (i.e., horizontal coordinate values of the terminal vector point B). This was further verified by comparison tests between value changes of the same parameters due to surgery. **Change in the Cobb's angle value was most strongly correlated with change in apical vertebral lateral deviation.**

In conclusion of the above, as a potentially new strategy for surgical correction, **the primary goal** might be a **most perfectly performed lateral translation**, with a ***relative*** **secondary importance of complete elimination of vertebral axial rotation**.

Although **vertebra vectors also mean a simplified and abstract visual presentation of the 3D spinal geometry**, they **preserve all information for vertebral size, 3D position, orientation, and rotation**. Vectors – placed inside a standard cartesian 3D coordinate system, **not requiring introduction of any auxiliary planes – represent a valid 3D system for true 3D measurements**, based on a patient-specific individual scale. While providing clear and comprehensible visual views – especially in horizontal plane top view – **they allow purely mathematical calculations** for 3D evaluation of spinal curves. As a result, the concept of vertebra vectors fulfill expectations of **SRS Working Group on 3-D Terminology of Spinal Deformity regarding a future 3D terminology of spinal deformities.**

6. SUMMARY AND SIGNIFICANCE OF NEW RESULTS

6.1 Application of the EOS 2D/3D system for 3D evaluation of adult lower limb deformities

6.1.1. Application of EOS 2D/3D lower limb examinations in routine clinical practice has been evaluated and confirmed by our workgroup in healthy adults and adult patients with hip and knee arthritis.

6.1.2. Application and clinical usability of lower limb sterEOS 3D reconstructions has been first evaluated by our workgroup worldwide, using medium-sized samples of healthy adults and adult patients with hip and knee arthritis.

6.1.3. Our workgroup has been first to measure and publish worldwide sterEOS 3D values of geometric lower limb parameters, using the same study samples.

Our results have been published in an article of a reputable international orthopedic journal, that became a frequently cited reference of the subject. *(Than P, Szuper K, Somoskeöy S, Warta V, Illés T. Int Orthop (SICOT) 2012;36:1291-1297.)* Our achievements served as a solid ground for later clinical and scientific activities of our Department with regards to lower limb EOS 2D/3D examinations and 3D reconstructions, with special emphasis on evaluations in children and adolescents.

6.2 Application of the EOS 2D/3D system for evaluation of lower limb fractures after osteosynthesis

6.2.1. Our workgroup was first to demonstrate worldwide, that biplanar lower limb X-ray images visualizing full extremities of both sides could be simpler and faster aquired by the EOS 2D/3D system for postoperative control of osteosynthesis results, while providing digital images with equal or better quality compared to conventional X-rays.

6.2.2. It has been confirmed that after osteosynthesis of lower limb fractures, substantial 3D information could be more easily aquired from EOS 3D reconstructions, with lower ionizing radiation dose compared to CT 3D examinations.

6.2.3. The EOS 2D/3D method has been successfully used for comparison of relevant parameters (such as length, mechanical and anatomical axis, torsion of the femur and tibia) of the healthy and operated limb.

6.2.4. It has been proven by our workgroup that parametric values of the operated and healthy leg based on lower limb 3D reconstructions are suitable for the evaluation of osteosynthesis results.

Our results have been reported in a national professional journal and at an international congress. *(Szuper K, Dömse E, Nőt L, Somoskeöy Sz, Than P. Magyar Traumatológia, Ortopédia, Kézsebészet és Plasztikai Sebészet 2013;56:119-126. Wiegand N, Kiss Z, Vámhidy L, Somoskeöy Sz. Injury, Int. Care Injured 2011;42:S28, P14.)* With respect to applications of EOS 2D/3D examination and EOS 3D reconstruction of lower limb fractures after osteosynthesis, our study had a pioneering importance. Thanks to its simplicity and speed, the method may be suitable for use in routine diagnostics.

6.3 Application of the EOS 2D/3D system for pre- and postoperative evaluation of spinal deformities

6.3.1. EOS 2D/3D full-spine examinations have been routinely used by our workgroup for radiological evaluation in adults, adolescents and children, either in healthy persons or patients with idiopathic and degenerative scoliosis. Postoperative assessment after correction surgery has been also carried out with this method. The number of examined cases in the period of 2007-2012 exceeded 2900, of which 450 cases have been examined after surgery.

6.3.2. SterEOS 3D full-spine reconstructions based on EOS images have been routinely performed with a total volume of 2700, of which 150-150 reconstructions have been done before and after surgery.

Based on these, our Department got an international reputation as an outstanding center. Our experiences have been summarized in a review article published in an international orthopedic journal that became a frequently cited reference. *(Illés T, Somoskeoy Sz. Int Orthop (SICOT). 2012;36:1325-1331.)* Significance of EOS 2D/3D system, visualization and analysis of sterEOS 3D reconstructions have been emphasized in national and international professional forums.

6.4 Evaluation and validation of EOS reconstructions for 3D characterization of spinal deformities

Validation of EOS 3D reconstruction parameters for evaluation of frontal and sagittal curves

6.4.1. Validation of frontal and sagittal curve parameters based on EOS 3D reconstructions against measurements by conventional 2D methods has been first performed by our workgroup worldwide, in a medium-sized study sample of normals and patients with spinal deformities of various type and degree.

6.4.2. Accuracy, reproducibility and reliability of the EOS 3D reconstruction method have been shown excellent. Conventional measurement methods have been documented to consistently fall short behind the EOS 3D reconstruction method.

Our results have been successfully published in a high-reputation international journal for spine surgery. *(Somoskeöy Sz, Tunyogi-Csapó M, Bogyó C, Illés T. Spine J. 2012;12:960-968.)* This article presumably contributed to the international recognition and wide adaptation of the new method in Orthopedics, that made this system a quasi standard at spine deformity centers.

Evaluation of horizontal plane view images of the EOS 3D reconstruction

6.4.3. Analysis of horizontal plane topview visualization of EOS 3D reconstructions has been introduced and made routine. Principles for a semi-quantitative evaluation have been also worked out.

6.4.4. Detailed analysis of the topview visualization has been performed in cases of various classification types and severity, and observed common and special features have been interpreted. Visual assessment has been supplemented by analysis of parametric data of 3D reconstructions.

Our results have been published in an esteemed international journal for spine surgery and our article recieved numerous citations. *(Illés T, Tunyogi-Csapo M, Somoskeöy S. Eur Spine J 2011;20:135-143.)* Analysis and interpretation of topview visualizations of EOS 3D reconstructions became routine in our own clinical practice and has been provided raison d'être at spinal deformity forums.

6.5 Analysis and validation of vector-based visualization of EOS reconstructions for 3D characterization of spinal deformities

6.5.1. A new concept of "vertebra vector" has been introduced by or workgroup that allows a simplified 3D visualization with vectors that replace the EOS 3D reconstructed spine and pelvis and makes parametric analysis based on mathematical calculations possible.

Validation of vertebra vector-based parameters for frontal and sagittal spinal curve measurements

6.5.2. Validation of frontal and sagittal curve parameters based on vector parameters from vector-based visualizations against measurements by conventional 2D methods has been performed, in a medium-sized study sample of normals and patients with spinal deformities of various type and degree.

6.5.3. Accuracy of the vector-based measurement method for coronal curves and thoracic kyphosis have been shown excellent. Our analysis has proven that the method exhibit a high reproducibility and an excellent reliability.

6.5.4. The inaccuracy in values for lumbar L_1-L_5 lordosis has been documented to be linked to L_5 vertebral wedging and connected with the difference in conventional and vector-based measurements method. The inherent error of conventional method may be eliminated by vector-based lordosis measurements.

Our results have been published in an article of a high-reputation international journal for spine surgery and has many citations. *(Somoskeöy Sz, Tunyogi-Csapó M, Bogyó C, Illés T. Spine J 2012; 12: 1052-1059.)* Based on our publications, our vector-based method is counted by a new 3D workgroup of Scoliosis Research Society for use in future multicentric studies with large patient samples.

Application of vertebra vectors for evaluation of deformity progression and results of surgical correction

6.5.5. Excellent suitability of the vector-based method has been demonstrated for visual and parametric evaluation of spinal deformity progression. A vector parameter representing the lateral deviation of the apical vertebra has been found the most sensitive indicator for progression.

6.5.6. Applicability of the vector-based method has been certified for visual and parametric evaluation of surgical corrections of spinal deformities. In contrast with expectations, not the change of Cobb's angle, but change in lateral deviation of the apical vertebra vector – representing lateral translation of the correction – has been shown the most sensitive and most accurate indicator for results of surgical correction.

Our observations have been published in an esteemed international journal for spine surgery. *(Illés T, Somoskeoy S. Eur Spine J. 2013; 22:1255-1263.)* Vector-based analysis is recommended for consideration in follow-up of spinal deformity progression, planning and evaluation of surgical correction under routine circumstances. Priority of the most sensitive vector parameter-indicator may result in a partial change in surgical correction strategy of spinal deformities.

7. BIBLIOGRAPHY

7.1. Publications that the Dissertation is based upon[3]

cumulative IF: 15,516; overall SJR: 8,648; independent/total citation: 201/221

1. Breakthrough in three-dimensional scoliosis diagnosis: significance of horizontal plane view and vertebra vectors
Illés T, Tunyogi-Csapo M, **Somoskeöy S**
Eur Spine J 2011; 20:135-143. *IF 1.965; SJR 1.404 Q1(Orthopedics and Sports Medicine); CI 52/59*

2. Geometrical values of the normal and arthritic hip and knee detected with the EOS imaging system
Than P, Szuper K, **Somoskeöy S**, Warta V, Illés T
Int Orthop (SICOT) 2012; 36:1291-1297.
IF 2.319; SJR 1.480 Q1 (Orthopedics and Sports Medicine); CI 42/46

3. Az EOS™ röntgengép elve és gyakorlati használata a mindennapi ortopédiai gyakorlatban
Illés T, **Somoskeöy Sz**
Orv Hetilap 2012; 153:289-295. *CI 2/4*

4. The EOS™ imaging system and its uses in daily orthopaedic practice
Illés T, **Somoskeoy Sz**
Int Orthop (SICOT) 2012; 36:1325-1331.
IF 2.319; SJR 1.480 Q1 (Orthopedics and Sports Medicine); CI 48/52

5. Clinical Validation of Coronal and Sagittal Spinal Curve Measurements Based on Three-Dimensional Vertebra Vector Parameters
Somoskeöy Sz, Tunyogi-Csapó M, Bogyó C, Illés T
Spine J 2012; 12:960-968.
IF 3.220; SJR 1.405 Q1 (Surgery); CI 15/16

6. Accuracy and Reliability of Coronal and Sagittal Spinal Curvature Data Based on Patient-Specific Three-Dimensional Models Created by the EOS 2D/3D Imaging System
Somoskeöy Sz, Tunyogi-Csapó M, Bogyó C, Illés T
Spine J 2012; 12:1052-1059.
IF 3.220; SJR 1.405 Q1 (Surgery); CI 31/31

---

[3] *ISI Impact Factor (IF), SCImago Journal Rank (SJR), independent/total citation (CI)*

7. EOS 2D/3D képalkotás alkalmazási lehetőségei az alsóvégtagon
Szuper K, **Somoskeöy Sz**, Than P, Illés T
Magyar Traumatológia, Ortopédia, Kézsebészet és Plasztikai Sebészet 2012; 55:203-212.

8. Comparison of scoliosis measurements based on three-dimensional vertebra vectors and conventional two-dimensional methods - Advantages in evaluation of prognosis and surgical results
Illés T, **Somoskeoy S**
Eur Spine J 2013; 22:1255-1263.
IF 2.473; SJR 1.474 Q1 (Orthopedics and Sports Medicine); CI 11/12

9. A csigolyavektor szerepe a gerincferdülés 3. dimenziójának megjelenítésében
Somoskeöy Sz, Illés T
Magyar Traumatológia, Ortopédia, Kézsebészet és Plasztikai Sebészet 2013; 56:41-51.

10. Femur és tibia diaphysis törések műtétet követő vizsgálata EOS 2D/3D röntgenkészülékkel
Szuper K, Dömse E, Nőt L, **Somoskeöy Sz**, Than P
Magyar Traumatológia, Ortopédia, Kézsebészet és Plasztikai Sebészet 2013; 56:119-126.

7.2. Other publications related to the subject of the Dissertation[4]

cumulative IF: 3,920; overall SJR: 2,466; independent/total citation: 21/27

1. XXI. századi csúcstechnológia a PTE Térségi Szűrő- és Diagnosztikai Központjában (TSZDK) II. rész
Battyány I, Járay Á, Illés T, Csete M, Lévai A, Szalai G, **Somoskeöy Sz**
IME Az egészségügyi vezetők szaklapja 2007; 6: 40-42.

2. EOS a klinikai gyakorlatban – Ultra alacsony dózisú, teljes test digitális röntgenfelvétel technikája, jelentősége, klinikai indikációja, információ tartalma
Lévai A, Battyány I, Járay Á, Csete M, **Somoskeöy Sz**, Illés T
IME Az egészségügyi vezetők szaklapja 2008; 7: 41-43.

3. Re: Sangole AP, Aubin CE, Labelle H, et al. Three-dimensional classification of thoracic scoliotic curves. Spine 2009; 34: 91-99. *(Letter to the Editor)*
Illés T, **Somoskeoy S**
Spine 2010; 35: 465-466. *CI 0/1*

4. A totál térdprotézis pozícionálása és az aszeptikus lazulás hosszú távú összefüggései
Than P, Létai B, **Somoskeöy Sz**, Horváth G
Magyar Traumatológia, Ortopédia, Kézsebészet és Plasztikai Sebészet 2011; 54:103-111.

5. Hibás pozícióban beültetett totál endoprotézis aszeptikus lazulása és revíziója
Than P, Szuper K, **Somoskeöy Sz**
Magyar Traumatológia, Ortopédia, Kézsebészet és Plasztikai Sebészet 2012; 55:79-84.

6. EOS 2D/3D képalkotás alkalmazási lehetőségei az alsóvégtagon
Szuper K, **Somoskeöy Sz**, Than P, Illés T
Magyar Traumatológia, Ortopédia, Kézsebészet és Plasztikai Sebészet 2012; 55:203-212.

7. Computer-generated, Three-Dimensional Spine Model From Biplanar Radiographs: A Validity Study in Idiopathic Scoliosis Curves Greater Than 50 Degrees
Carreau JH, Bastrom T, Petcharaporn M, Schulte C, Marks M, Illés T, **Somoskeöy S**, Newton PO
Spine Deformity 2014; 2:81-88.
SJR 0.365 Q3 (Orthopedics and Sports Medicine); CI 15/15

---

[4] *ISI Impact Factor (IF), SCImago Journal Rank (SJR), independent/total citation (CI)*

8. Az EOS 2D/3D System alkalmazhatóságának vizsgálata a szabad alsóvégtag anatómiai és biomechanikai paramétereinek mérésére gyermekkorban
Schlégl ÁT, Szuper K, **Somoskeöy S**, Than P
Orv Hetilap 2014; 155:1701-1712. *CI 0/2*

9. A csípőízület 3D modellezése gyermekkorban
Schlégl ÁT, Szuper K, **Somoskeöy S**, Than P
Magyar Traumatológia, Ortopédia, Kézsebészet és Plasztikai Sebészet 2014; 57:169-179.

10. Three-dimensional quantitative analysis of the proximal femur and the pelvis in children and adolescents using an upright biplanar slot-scanning X-ray system
Szuper K, Schlégl ÁT, Leidecker E, Vermes C, **Somoskeöy S**, Than P
Pediatr Radiol 2015; 45:411-421. *IF 1.530; SJR 0.593 Q2 (Radiology, Nuclear Medicine and Imaging); CI 3/5*

11. Az alsóvégtag tengelyállásának vizsgálati lehetőségei - Tapasztalataink az új EOS 2D/3D technológiával
Schlégl AT, Szuper K, **Somoskeöy S**, Than P
Magyar Traumatológia Ortopédia Kézsebészet Plasztikai Sebészet, 2015;58:127-139.

12. Three-dimensional radiological imaging of the normal lower limb alignment in children
Schlégl ÁT, Szuper K, **Somoskeöy S**, Than P
Int Orthop (SICOT) 2015; 39:2073-2080.
IF 2.390; SJR 1.508 Q1 (Orthopedics and Sports Medicine); CI 3/4

7.3. Citable abstracts related to the subject of the Dissertation[5]

cumulative IF: 4,326; overall SJR: 4,396

1. 2009 Argospine best poster award : Visualization and evaluation of spinal 3D geometry in scoliosis using EOS 2D/3D imaging: first-year clinical data prove the significance of the horizontal plane view
Somoskeoy S, Dubousset J, Illes T
ArgoSpine News & Journal 2009; 21: 13.

2. Clinical Evaluation Of EOS 2D/3D Ultra Low-Dose Radiation System In Lower Limb Orthopedic Applications: Significance And Clinical Value Of True 3D Measurements And 3D Surface Reconstructions
Somoskeoy Sz, T Illés, and P Than
J Bone Joint Surg Br Proceedings, 2010; 92-B: 499. *IF 2.351; SJR 2.897 Q1 (Orthopedics and Sports Medicine)*

3. The postoperative clinical evaluation of femur and tibia shaft fractures with EOS 2D/3D ultra low-dose radiation system
Wiegand N, Kiss Z, Vámhidy L, **Somoskeöy Sz**
Injury, Int. Care Injured 2011; 42:S28, P14. *IF 1.975; SJR 0.920 Q1 (Orthopedics and Sports Medicine)*

4. Significance of vertebral lateral ejection versus axial rotation in pre- and postoperative evaluation of adolescent idiopathic scoliosis - a vertebra vector study
Somoskeöy S, Tunyogi-Csapó M, Illés T
Journal of Children's Orthopaedics, 2012; 6 Suppl: 35-55. *SJR 0.579 Q2 (Orthopedics and Sports Medicine)*

7.4 Patent related to the subject of the Dissertation

A Method And A System For Multi-Dimensional Visualization Of The Spinal Column By Vertebra Vectors, Sacrum Vector, Sacrum Plateau Vector And Pelvis Vectors
Illés T, **Somoskeöy S**
US Patent 8,885,899 B2 (2014)
patents pending WO/2011/092531 A1 (2011); CA27884545 A1 (2011); EP2528504 (2011)

---

[5] *ISI Impact Factor (IF), SCImago Journal Rank (SJR)*

8. ACKNOWLEDGEMENTS

First and foremost, I'd like to thank my former mentor, **Dr. Miklós Kellermayer** "Tanár úr" for getting me aquinted with pleasures of research, passions of scientific work and implanted me with a desire to accomplish and create something new.

I am forever grateful to my tutor and boss, **Dr. Péter Than**, for his support through years with patience, understanding and helpfulness, and for creating relaxed personal and professional circumstances helping completion of my dissertation. His encouragement and professional advices were invaluable to me. A significant part of work presented in this dissertation are the results of our joint endeavor.

I am indebted to my former boss, **Dr. Tamás Illés**, for inviting me to this adventure in the Spring of 2007 – one full with stressful work, lots of challenges, excitements and pleasures, all of that would not be possible without the EOS 2D/3D system. Another significant part of work documented in this thesis was based on our joint efforts and our intellectual property.

I express my friendly thanks to my colleagues **Dr. Miklós Tunyogi Csapó**, **Dr. Csaba Bogyó** and **Dr. Máté Burkus** for their persistent participation in the spine 3D reconstruction studies.

I am thankful to my colleagues **Dr. Kinga Szuper** and **Dr. Ádám Schlégl** for their selfless cooperation in lower limb studies, as well as to my colleague **Dr. Ian O'Sullivan** for his valuable contribution to the introduction chapter of this dissertation.

I thankfully acknowledge **Dr. Norbert Wiegand** for his idea of the traumatological lower limb study, and **Dr. Eszter Dömse** for her diligent participation in its implementation.

I truly appreciate activities of **Dr. István Battyány** and his **co-workers at the Radiology Department** in performing EOS examinations and operating the equipment.

I am beholden to managers, former and current co-workers of **EOS Imaging S.A., Paris, France**, for their helpful collaboration and support between 2007-2012.

I passionately thank **Vanda** for her love, encouragement and compassion – this dissertation could not have been completed without her.

Last but not least, I want to dedicate this work to my sons **Tamás**, **Balázs** and **Ákos**.