2020 IEEE International Conference on Bioinformatics and Biomedicine (BIBM)

Supporting Diagnosis and Treatment of Scoliosis: Using Augmented Reality to Calculate 3D Spine Models in Real-Time - ARScoliosis

Saša Ćuković
Institute for Biomechanics - IfB
ETH Zurich
Zurich, Switzerland
sasa.cukovic@hest.ethz.ch
https://orcid.org/0000-0003-0525-2197

Radu Emanuil Petruse
Lucian Blaga University of Sibiu
Sibiu, Romania
radu.petruse@ulbsibiu.ro
https://orcid.org/0000-0002-4081-1161

Lea Buchweitz
Heilbronn University
Heilbronn, Germany
lbuchwei@stud.hs-heilbronn.de
https://orcid.org/0000-0002-2189-9751

Gerrit Meixner
UniTyLab
Heilbronn University
Heilbronn, Germany
gerrit.meixner@hs-heilbronn.de
https://orcid.org/0000-0001-9550-7418

2020 IEEE International Conference on Bioinformatics and Biomedicine (BIBM) 978-1-7281-6215-7/20/$31.00 ©2020 IEEE DOI: 10.1109/BIBM49941.2020.9313200

***Abstract*—*Scoliosis is a complex spinal disorder that mostly affects adolescents and younger population. To avoid and reduce harmful radiation techniques in adolescent idiopathic scoliosis investigation and follow-ups, a novel non-invasive approach is highly recommended and needed in clinical practice. In this paper ARScoliosis application to diagnose, visualize and document spinal condition and particularly adolescent idiopathic scoliosis in real time is presented. This ARScoliosis application is developed in Unity 3D, a game engine, and allows non-invasive quantification of posture and spinal deformity using recently available non-ionizing wide-angle depth sensor Microsoft Azure Kinect DK as a diagnostic medium. Parametric and scalable 3D model of the spine is registered to the internal spinal alignment extracted from the anatomical landmarks and joints in real time and visible over the specific patient. It is envisioned that ARScoliosis will support monitoring of scoliosis after applied therapy and include more diagnostic parameters, after final testing and validation against standard X-Ray imaging modalities.*

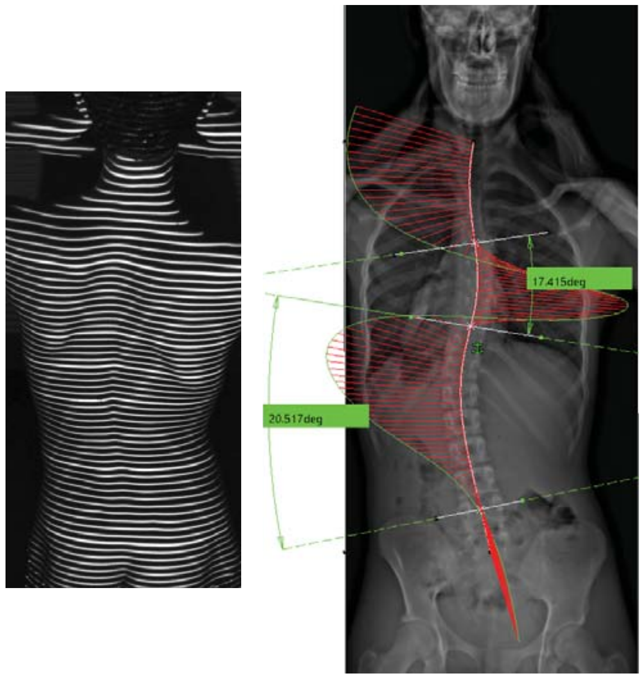
***Keywords*—*Augmented Reality, Spinal Disorder, Scoliosis Diagnosis, Visual Inspection.*

I. Introduction

Scoliosis is a highly complex 3D musculoskeletal disorder of the spine that greatly influences the patient's health and quality of life. Scoliosis affects 0.47–5.20% of the global population [1], and almost 80-90% of the cases develop for an unknown reason (idiopathic) [2]. Adolescent idiopathic scoliosis (AIS) is defined as a deformation of the spine by an angle of more than 10º, measured on standing radiographs, using the Cobb technique [3].

The main drawback of traditional radiographic (RAD) methods in AIS assessment (Figure 1b) is their harmful effect on the young population, especially due to multiple radiation exposures while monitoring progression of the disease, which increases the risk for malignancy development later in life. However, it is mandatory for patients with AIS to be examined every 3–6 months to monitor the curvature's progression [4] (Figure 1a). The clinical goal and priority are therefore to avoid or reduce application of those methods in AIS monitoring [5] with a clear preference for non-invasive techniques based on visual examination of the patient's trunk and external deformity measures [5], [6].

In recent years, innovative marker-based 3D optical systems have been considered as alternatives to RAD imaging (e.g., Vicon, Moirè Topography, Quantec Spinal Imaging System, Integrated Shape Imaging System) due to their ability to produce a non-invasive estimation of the external back profile, hence allowing the calculation of external parameters of AIS [7], [8]. These systems use the position of markers placed on anatomical landmarks on the subject's skin, to reconstruct the spinal posture, but such techniques are subject to high levels of errors due to soft tissue artefacts.



a) b)

Fig. 1. Evaluating scoliosis: a) visual inspection - optical diagnosis, b) traditional radiographic assessment through measuring primary and secondary Cobb angles on X-ray images.

A novel 3D optical method, e.g. rasterstereography (RST), is a less expensive, non-ionizing technique which estimates deformity-related changes of the patient's back using only light as a medium [9]. Unfortunately, none of these methods visualize the 3D model of the patient-specific spine and particularly its structure in real time, statically or dynamically.

Recently, applications of non-ionizing Augmented Reality (AR) or Virtual Reality (VR) technologies showed promising results in supporting medical decisions, diagnosis and therapy.

1) Medical Augmented Reality applications review

AR, a technology which according to Gartner's hype cycle [10] has passed from the emerging technology class to a more mature state, can be the key technology to enable the visualization of 3D patient-specific models in the physical environment e.g. 3D spinal model superimposed over the patients' dorsal surface.

In the recent years, the interest on medical AR applications has been escalating, mainly due to the recent hardware and software development which enabled a various range of AR applications and improved the accessibility to this technology to an expansive group of users. One of the most accurate sources where the popularity of AR applied for medical purposes can be observed is the PubMed database (Figure 2) where 2389 papers include "Augmented Reality" in the title from which 73 papers treat the subject AR applied for spinal affections and treatment procedures, mainly focused on surgical procedures.

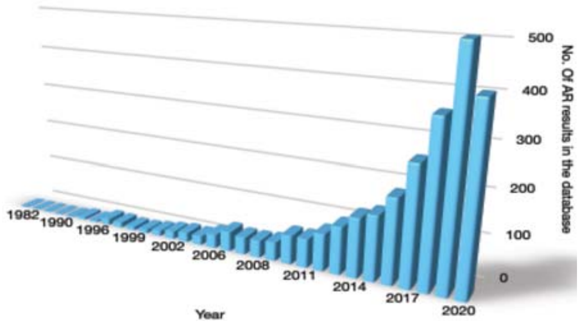


Fig. 2. PubMed database AR results by year [11].

AR popularity is not the only characteristic which evolved in the past decades, if at its earliest development phases AR was used to provide auxiliary information during medical procedures (e.g. a live video with ultrasound images [12], MRI and CT data [13] [14]), nowadays, the challenge is to use AR to access and visualize real-time patient-specific data superimposed with the highest accuracy [15]. Some researchers suggest that in the near future, AR will replace traditional medical tools such as microscopes, navigation and display equipment etc. [16]. As we analysed multiple research papers and use cases, we identified that, currently, the most advanced AR applications are used to aid clinicians, predominantly during and while planning interventional procedures. In [17] the authors reviewed the latest commercial and research medical AR applications. Among these applications is [18] which is currently testing an AR tool able to offer real-time patient-specific anatomical information.

In the field of spinal disorders AR applications are mainly developed to support surgical procedures. One of the first AR applications developed to support and navigate scoliosis surgery was developed in 1995 [19]. Since then, due to the technical advances, there are numerous solutions and applications that use AR for spinal corrective therapies [20]. The latest innovation in the spinal surgery has been made by Augmedics [21] which used their "xvision Spine" system in a world's first minimally invasive spine surgery performed on June 15 2020 [22]. As for the spinal deformity evaluation and diagnosis, a few AR based studies were found, mainly due to the fact that an AR application will not suffice if it is not used by well-trained clinicians. Few AR concepts and solutions were found in domain of spinal 2D visualization and diagnosis, [23], [24], [25]. In [25] an AR framework for spinal disorders diagnosis is presented as well as full 3D spinal model. The lack of novel research and reliable solutions in this field is what motivated us to develop a new diagnostic and visualization application – AR Scoliosis. Moreover, we could not identify any solution which is able to track the patient's anatomical landmarks in real-time and to superimpose a dynamic patient-specific spinal 3D model which is able to extend the intervals between X-ray images thus reducing the radiation as much as possible.

II. Methodology

To develop an AR application for real-time visualization of an idiopathic 3D spinal deformity we used a combination of specific hardware and software to perform four development steps as described in figure 3.

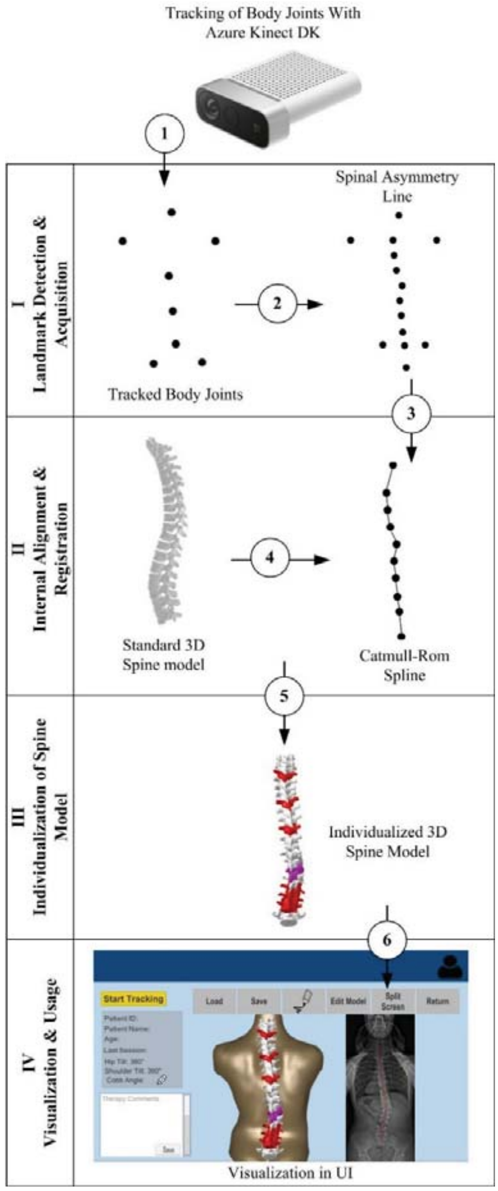
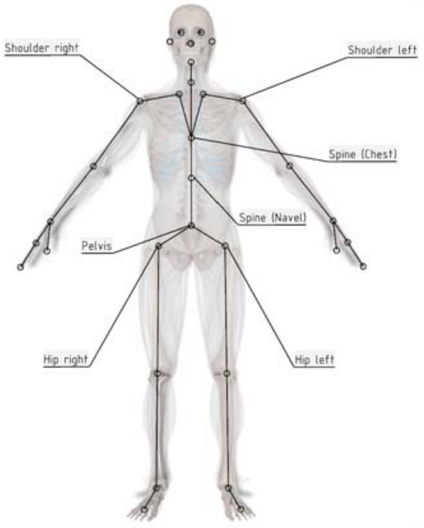
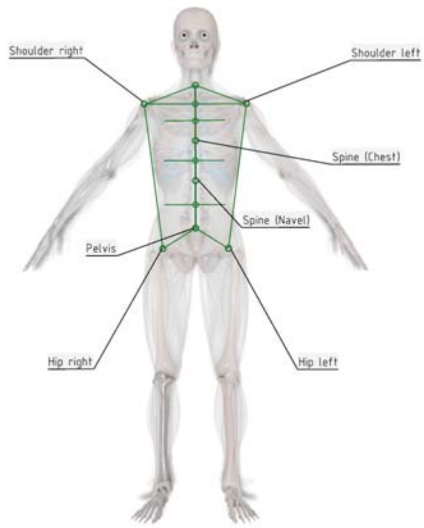


Fig. 3. Development phases: I) Landmark detection and acquisition, II) Initial alignment and registration, III) Individualization of the spinal model, IV) Visualization, GUI and usage.



a)



b)

Fig. 4. Anatomical landmarks and joints from the Body Tracking Function of the Azure Kinect DK: a) default as detected by Kinect, b) additional points created to improve accuracy.

As depicted in figure 3 phase I, the first step of the ARScoliosis application is to detect necessary landmarks from the physical environment (e.g. from the patient's body). Using these landmarks, the 3D spinal model is modified accordingly to the automatically registered internal spinal alignment (Figure 3 phase II and III). The final step is to include all this information into a user-friendly interface which can be used by clinicians.

A. AR application requirements

In order to develop a functional AR application three major requirements, have to be satisfied:

1) Hardware

To fulfil abovementioned tasks in the development process, stationary PC and Microsoft Azure Kinect DK as an external acquisition device were used. This is due to the following reasons:

- Microsoft Azure Kinect DK uses heavy computational libraries and powerful PC with a large screen. This is beneficial for detailed diagnosis and provides a good accessibility and overview over the numerous functionalities of the user interface (UI).
- Microsoft Azure Kinect DK is a development kit which includes relevant components for this task such as a wide-angle depth sensor (depth data), a 4K RGB video camera (colour data) and an inertial measurement unit (orientation sensor). Most importantly, the Microsoft Azure Kinect DK has a Body Tracking SDK included, which can track human joints at runtime.

2) Software

To develop an application for scoliosis visualization and to calculate important diagnostic parameters the game engine Unity 3D (C#) is used. It provides a good integration of the Microsoft Azure Kinect DK libraries, as well as cross-platform development for Microsoft Windows, Android and iOS. The software can be easily expanded with a condensed, mobile version for smartphones or tablets.

3) Used landmarks

The following eight out of 32 available joints from the Body Tracking Function of the Microsoft Azure Kinect DK were used to calculate the asymmetry line: 1) Neck, 2) Shoulder right, 3) Shoulder left, 4) Spine_Chest, 5) Spine_Naval, 6) Pelvis, 7) Hip_right, 8) Hip_left (Figure 4 a).

Additional landmarks and joints could be added to allow better modelling and more precise localization of specific vertebra, according to statistical models available in literature [26] (Figure 4 b).

B. AR application development

To meet all clinicians' needs a reliable 3D model of the spine and the visualization in AR must be developed. To achieve this, we have done the following:

1) Extraction of asymmetry line

The asymmetry line on back (dorsal) surface was enriched with six additional data points calculated using the shoulder-hip vectors bilaterally. The centre of the connecting line between the shoulder-hip vectors was calculated on 10, 20, 40, 50, 70 and 85 percent of the vectors. For example, the joints *shoulder_left* and *shoulder_right* were connected and the centre of this vector used as an additional value for the asymmetry line between the neck and *spine_chest* joint which was detected by the Azure Kinect.

2) 3D model creation and positioning

The 3D model of a spine was calculated based on the back-asymmetry line. Each data point of the spinal line (both, automatically tracked joints, as well as additionally calculated points) represented a point of a Catmull-Rom spline. A Catmull-Rom spline is an interpolating spline with one point at each end of the curve and several control points in between. 3D models of twenty vertebrae (C5 to L5) [27] were attached to the Catmull-Rom spline using the control points of the automatically tracked joints and the calculated additional points.

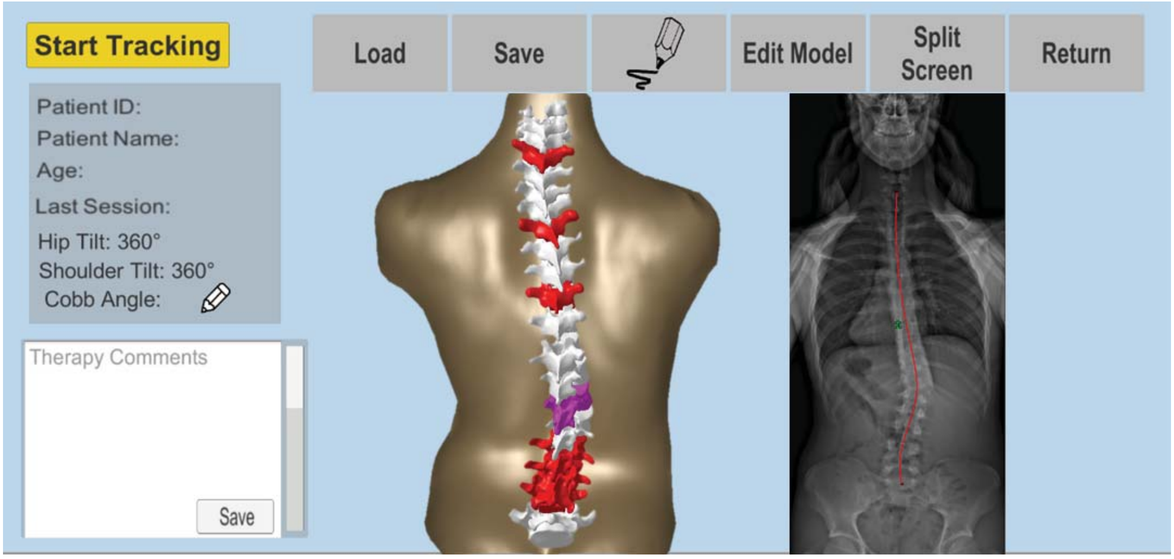


Fig. 6. GUI of the ARScoliosis application for 3D visualization, diagnosis and archaiving records on subject specific posture or spinal pathologies including another modalities e.g. X-ray image.

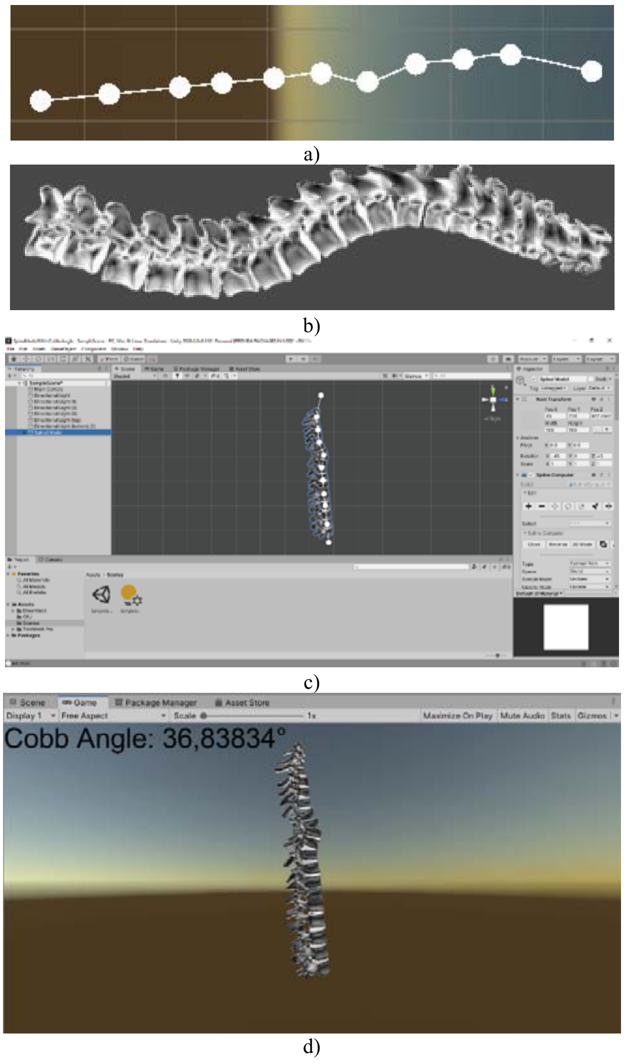


Fig. 5. 3D model registration: a) initial set of control points of the internal spinal alignment, b) registerable and scalable 3D generic model of the human spine, c) registration process in Unity 3D, d) 3D subject-specific model of the spine and Cobb angle.

To implement 3D model generation, "Dreamteck splines v2.01" free version of the Package is used [28]. However, there are some open issues:

a) individual rotation of each vertebrae toward the patients' dorsal surface is more precisely determined than using other interpolation methods (e.g. Bezier curves), however not yet optimal.

b) dynamic adaptation of the spine model with movements of the patient. (adaptations to randomly changing control points each 0.03sec was verified).

3) Model Registration

The tracked and calculated coordinates of the joints were directly used to initialize the Catmull-Rom spline and to attach the vertebrae accordingly. This process is performed through 3D rigid registration presented at figure 5.

In the registration process, the main parameter of posture and spinal deformity e.g. primary and/or secondary Cobb angle is calculated and presented to the user. The Cobb angle can be calculated dynamically from the 3D spine model by adapting the traditional way of Cobb angle calculation, based on 2D X-ray images to the 3D model meaning that:

- The application must locate the most tilted vertebra at the top of the curve and draw a parallel line to the superior vertebral end plate.
- The application must locate the most tilted vertebra at the bottom of the curve. Then draw a parallel line to the inferior vertebral end plate.
- The application must erect intersecting perpendicular lines from the two parallel lines.
- The angle formed between them is Cobb angle.

This method is easier and more accurate compared to the traditional way, because the rotation data of each vertebra is already documented. After iterating over all vertebrae, and calculate the angle between two successive vertebrae, the biggest degree angle should be the primary Cobb angle.

4) Integration into an interactive user interface

The interactive UI of ARScoliosis integrates the tracking and calculation of the 3D spine model, as well as numerous features to facilitate regular check-ups of AIS. In that

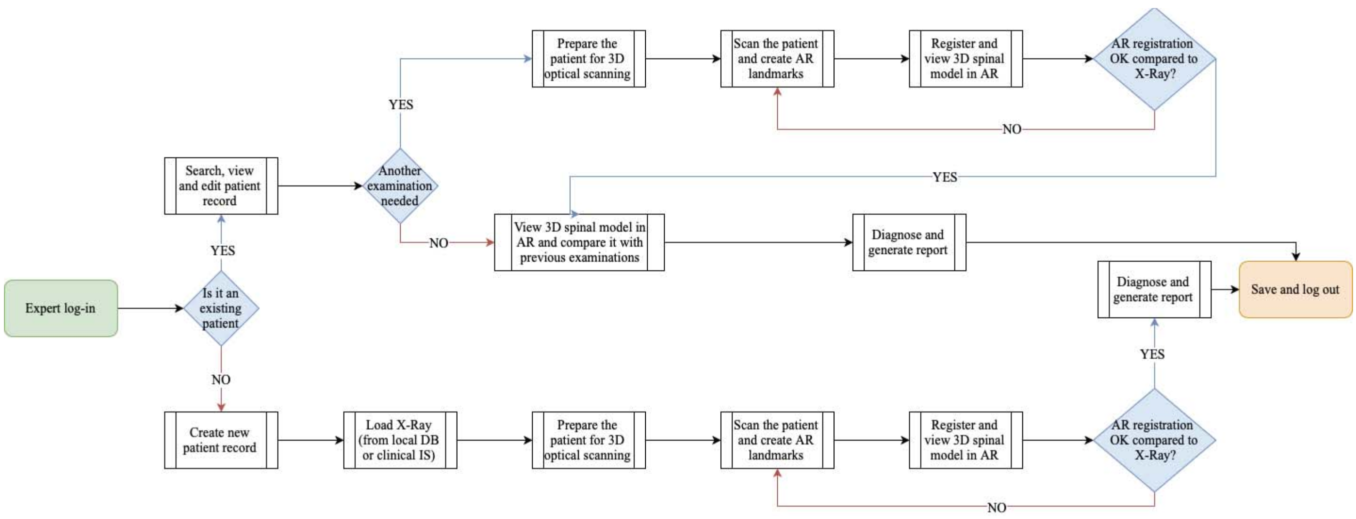


Fig. 7. Use Case Diagram with patient management features embedded in the ARScoliosis UI and platform.

sequence, the main goal of this non-invasive application is to extend the intervals between X-ray images to reduce radiation as much as possible.

Via video stream of the Microsoft Azure Kinect DK the body of the patient is tracked, and a 3D model of the patient-specific spine is displayed in real-time on the video stream or a static image (i.e. a screenshot), as it is depicted in figure 6.

Based on five medical expert interviews (spinal surgeons and physicians), the UI provides several features, such as free-hand drawing to highlight and annotate parts of the spine, a screenshot function that can store the free-hand annotations, a tool to examine the spine in detail (i.e. turning the spine and zooming in or out), a field where notes can be taken and a feature that allows to compare X-ray images with the real-time calculated 3D model of the spine. Further, the application is connected to a database to store patient data, the individual clinical history, as well as X-ray images or (annotated) screenshots of the dynamically calculated spine, or specific parameters, such as Cobb angle or Risser sign.

C. *Use Case Diagram*

The use case diagram in figure 7 clarifies which users (physicians and physiotherapists) are intended to work with ARScoliosis in the future and how their workflow could look like. Medical experts are the main user group intended to use the system, dealing with two different use cases. Primarily, if a patient is not yet part of the system, the expert can insert or connect all relevant data to calculate a first 3D model of the patient's distorted spine. After creating a record about a new patient and saving all data to the database, the expert can start the diagnosis process and when finished, he can leave the process and close the software or explore the record of an existing patient.

Secondly, for existing patients, the spine model can be edited, zoomed, rotated, a new calculation of the spine model can be initiated, a screenshot can be taken, or his specific model can be compared to corresponding X-Ray image.

The database was implemented with MySQL and the phpMyAdmin database using MAMP. This database can be connected from the Unity C# Script over a php-File to the localhost database on the web.

III. Results and Discussions

Based on interviews conducted with five medical experts, in the development phase four of them said that they have already used devices that can tracks the patient's back using laser or optical technology. However, these devices are very unreliable and expensive and normally diagnosis is usually performed manually (e.g. bend-forward test, or hip/shoulder tilt) or using conventional radiography.

So far none of these technological devices (optical scanners) are regularly used for diagnosis, therapy or regular check-ups. A simpler device and software that would help to monitor AIS development would be highly appreciated and could expand intervals between harmful X-Ray follow-ups.

All medical experts said that an appealing UI would be helpful to show the patient how their spine looks and to simulate how postural changes and exercises could improve it. The visualization in ARScoliosis could furthermore improve patient's adherence to the therapy.

Based on the needs of the medical experts we developed an AR application in combination with Microsoft Azure Kinect DK. Catmull-Rom splines were used to simulate 3D spinal model, because the individual rotation of each vertebrae is more precisely determined than with Bezier curves and also the scaling of the spinal model is more convenient with Catmull-Rom splines, as the vertebrae scale dynamically in relation to the up or down scaling factor of the spline.

Ongoing testing in clinical practice will allow us to evaluate its precision and to validate generated parameters and patient-specific model against standard modality like CT or bi-planar radiographs.

Moreover, ARScoliosis can be adopted for industrial purposes. For example, during a training process for manual assembly operations, this application can be used to monitor the ergonomic parameters and range of the motion. In the future, we plan to use this application together with the innovative training station developed in the DiFiCIL project [29].

IV. Conclusions

In this research paper we present a concept for an application called ARScoliosis aimed to enable the detection, diagnosis and visualization of AIS using AR. It combines cutting-edge spatial computing equipment with AR technologies to improve the diagnosis and monitoring process by reducing the need for standard X-Ray-based AIS investigation. ARScoliosis, thus being in a development stage, can be a good base for supporting diagnosis and treatment of AIS in a clinical environment.

Future work implies testing the application on at least fifty patients to validate its efficiency against conventional X-Ray diagnosis methods. Also, more functionalities should be added to this application, such as the possibility to calculate additional internal and external parameters of deformity and posture.

Acknowledgment

We would like to thank the group of students from UniTyLab at Heilbronn University who contributed to this research within the INIAT course.

This work is supported through the DiFiCIL project (contract no. 69/08.09.2016, ID P_37_771) co-founded by ERDF through the Competitiveness Operational Programme 2014-2020 and by the Serbian Ministry of Science and Technological Development (451-03-68/2020-14/200378).

References

[1] K. M. Rafael, H. Senyurt and R. Krauspe, "Epidemiology of adolescent idiopathic scoliosis," *Journal of children's orthopaedics,* vol. 7, no. 1, pp. 3-9, 2013.

[2] Ć. Saša, "PhD Thesis: Non-rigid registration of sculptured surfaces in Internet environment," Kragujevac, 2015.

[3] C. J. Robert, "Outline for the study of scoliosis," *The American Academy of Orthopedic Surgeons Instructional Course Lectures,* vol. 5, pp. 261-275, 1948.

[4] P. Patias, T. B. Grivas, A. Kaspiris, C. Aggouris and E. Drakoutos, "A review of the trunk surface metrics used as Scoliosis and other deformities evaluation indices," *Scoliosis,* vol. 5, no. 12, pp. 1-20, 2010.

[5] K. Amin, L. M. Westover, E. C. Parent, M. Moreau, M. El-Rich and S. Adeeb, "Surface topography asymmetry maps categorizing external deformity in scoliosis," *The Spine Journal,* vol. 14, no. 6, pp. 973-983, 2014.

[6] D. Burkhard, "Rasterstereography measurement of scoliotic deformity," *Scoliosis,* vol. 9, no. 22, pp. 1-18, 2014.

[7] G. C. Lam, D. L. Hill, L. H. Le, J. V. Raso and E. H. Lou, "Vertebral Rotation Measurement: A Summary and Comparison of Common Radiographic and CT Methods," *Scoliosis,* vol. 3, no. 16, pp. 1-10, 2018.

[8] R. M. C. Aroeira, J. S. Leal and A. E. d. M. Pertence, "New method of scoliosis assessment: preliminary results using computerized photogrammetry," *Spine,* vol. 36, no. 19, pp. 1584-1591, 2011.

[9] S. Schülein, S. Mendoza, R. Malzkorn, J. Harms and A. Skwara, "Rasterstereographic evaluation of interobserver and intraobserver reliability in postsurgical adolescent idiopathic scoliosis patients," *Journal of Spinal Disorders & Techniques,* vol. 26, no. 4, pp. E143-9, 2013.

[10] Gartner, Inc., "Hype Cycle Research Methodology," Gartner, 2020. [Online]. Available: https://www.gartner.com/en/research/methodologies/gartner-hype-cycle. [Accessed August 2020].

[11] National Center for Biotechnology Information, "PubMed," 2020. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov. [Accessed August 2020].

[12] T. Sielhorst, M. Feuerstein and N. Navab, "Advanced Medical Displays: A Literature Review of Augmented Reality," *JOURNAL OF DISPLAY TECHNOLOGY,* vol. 4, no. 4, pp. 451-467, 2008.

[13] W. Grimson, G. Ettinger, S. White, P. Gleason, T. Lozano-Perez, W. Wells and R. Kikinis, "Evaluating and Validating an Automated Registration System for Enhanced Reality Visualization in Surgery," in *First International Conference, CVRMed '95*, Nice, 1995.

[14] J. Zhao, A. Colchester, C. J. Henri, D. Hawkes and C. Ruff, "Visualisation of Multimodal Images for Neurosurgical Planning and Guidance," in *First International Conference, CVRMed '95*, Nice, 1995.

[15] W. O. C. López, P. A. Navarro and S. Crispin, "Intraoperative clinical application of augmented reality in neurosurgery: A systematic review," *Clinical Neurology and Neurosurgery,* vol. 177, pp. 6-11, 2019.

[16] P. Vávra, J. Roman, P. Zonča, P. Ihnát, M. Němec, J. Kumar, N. Habib and A. El-Gendi, "Recent Development of Augmented Reality in Surgery: A Review," *Journal of Healthcare Engineering,* p. 1–9, 2017.

[17] M. K. Southworth, J. R. Silva and J. N. A. Silva, "Use of extended realities in cardiology," *Trends in Cardiovascular Medicine,* vol. 30, no. 3, pp. 143-148, 2020.

[18] "SentiAR - Realtime Clinical AR," [Online]. Available: https://sentiar.com. [Accessed August 2020].

[19] B. Peuchot, A. Tanguy and M. Eude, "Virtual Reality as an Operative Tool During Scoliosis Surgery," in *First International Conference, CVRMed '95*, Nice, 1995.

[20] J. S. Yoo, D. S. Patel, N. M. Hrynewycz, T. S. Brundage and K. Singh, "The utility of virtual reality and augmented reality in spine surgery," *Ann Transl Med 2019,* vol. 5, no. 7, 2019.

[21] "xvision Spine System," [Online]. Available: https://augmedics.com. [Accessed August 2020].

[22] "Business Wire," 2020. [Online]. Available: https://www.businesswire.com/news/home/20200617005352/en/Dr.-Frank-Phillips-World-Augmented-Reality-Surgical. [Accessed August 2020].

[23] O. J. Choudhry, S. N. Mundluru, C. Morley, F. Ahmed, A. J. Buckland and A. K. Frempong-Boadu, "Augmented Reality for Evaluation of Spinal Deformity and Spinal Pathologies," *NASS 32nd Annual Meeting Proceedings, The Spine Journal,* 2017.

[24] S. A. Nash, J. R. White, A. Galloway and J. L. Claypool, "Augmented reality diagnosis guidance". US Patent US20180256258A1, 03 03 2020.

[25] Ć. Saša, P. Frieder, U. Antonio, D. Goran, L. Vanja, F. Michele and L. Tanja, "Conceptual Augmented Reality Framework for Spinal Disorders Representation and Diagnosis," in *2nd Regional Conference Mechatronics in Practice and Education - MECHEDU2013*, Subotica, 2013.

[26] M. Panjabi, V. Goel, T. Oxland, K. Takata, J. Duranceau, M. Krag and M. Price, "Human lumbar vertebrae. Quantitative three-dimensional anatomy.," *Spine,* vol. 17, no. 3, pp. 299-306, 1992.

[27] S. Ćuković, W. Taylor, V. Luković, I. Ghionea, K. Baizid, J. Iqbal and S. Karupppasamy, "Rigid 3D Registration Algorithm for Localization of the Vertebral Centroids in 3D Deformity Models of Adolescent Idiopathic Scoliosis," *Journal of Computer-Aided Design & Applications,* vol. 17, no. 6, pp. 1313-1325, 2020.

[28] "Unity Asset Collection," [Online]. Available: http://unityassetcollection.com/tag/unity-dreamteck-splines-free-download/. [Accessed May 2020].

[29] B.-C. Pîrvu, "Conceptual Overview of an Anthropocentric Training Station for Manual Operations in Production," in *Balkan Region Conference on Engineering and Business Education* , Sibiu, 2019.