A RESEARCH FRAMEWORK CONCEPT ADAPTED TO MOIRÉ IMAGING IN SCOLIOSIS

Doctoral (PhD) Theses

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CONTENT

List of Abbreviations

2D or **2-D**	two-dimensional (or bidimensional)
3D	three-dimensional
CAT	Contour Analysis Tool
FST	Fringe Segmentation Tool
ICT	Information and Communications Technology
KPI	key performance indicator
MF	moiré fringe
MI	moiré image
MITS	Moiré Imaging Tool for Scoliosis
MM	moiré method
MPT	Moiré Production Tool
MT	moiré topography
PM	projection moiré
PMT	projection moiré technique
PSNR	peak signal-to-noise ratio
QRT	quasi-real-time
R&D	research and development
RMS	root mean square
ROI	region of interest
SD	standard deviation
sec.	section
SM	shadow moiré
SMT	shadow moiré technique
SOAR	Strengths, Opportunities, Aspirations, and Results
SWOT	Strengths, Weaknesses, Opportunities, and Threats
UI	user interface
XOR	eXclusive OR (Boolean logic operation)

I. Introduction

The diagnostics of spinal deformities has long been in the focus of medicine. Postural deviations of children and adolescents are an important medical and social issue, where research indicates a disturbing phenomenon of the frequent appearance and progression of irregularities. Consequently, screening is considered as the most important factor in preventing deformity from progressing.

For diagnosing body posture, objective methods are required. Today the gold standard for identifying changes in the spine position is the radiographic examination. Disadvantages of X-ray imaging such as cost, time and repetition demands, tools and environmental conditions required and radiation exposure imparted to the patient, are not negligible, and justify methodological research of such moiré technique or moiré topography (MT), that can lead to fast, cost-effective and non-ionizing diagnostic imaging of the spine.

MT is based on optical phenomena by which moiré images (MIs) are created, comprising alternating bright and dark fringes. The pattern formed by moiré fringes (MFs) on the surface of an object is then applied for subsequent analysis. The primary advantages of MT are that it is non-invasive, fast, free of harmful radiation, portable and cost-effective. MT is used for the detection of early stages of scoliosis and different deformities of the spine. However, further research is required to improve the analysis of the topograms. An algorithm based on MT that is proved suitable for calculating the curvature angle of the spine may also complement or substitute harmful X-ray imaging.

The workload required for evaluation of MIs is, however, not inconsiderable; some researchers see the best solution for that in an automatic system. Processing of MIs requires several unique solutions that are influenced by the optical arrangement, nature of noise and detection, and applied illumination. Therefore, implementing a fully automated image analysis and evaluating solution is a challenging, nevertheless desired objective in the field.

These conditions induced this PhD research that aims (I) to summarize the theory of the moiré method (MM), and (II) to develop a software-based research framework concept and fringe segmenting methods adapted to moiré imaging in scoliosis as a manual/semi-automatic tool for MF detection and mathematical-geometric calculations.

II. Aims and Methods

The basic purpose of the research is to provide feasible and realistic answers for challenges introduced in Theses 1-5. This dissertation is also meant to elaborate on certain work packages of the proposed research framework concept adapted to scoliosis, to be developed in postdoctoral research. The aims and methods of the research are summarized as listed below (a-f).

(a) To present the theory, history and medical technical application of MM describing the two main moiré techniques, the shadow and projection moiré in detail.

Method: Reviewing literature selected in different databases, such as Scopus, PubMed, Science Direct and IEEE Xplore®.

(b) To provide a step-by-step guide for performing moiré imaging in scoliosis using digital projection MM for supporting future measurements.

Method: Reviewing, generalizing and completing the process of a digital projection moiré technique presented by BALLA et al. [1].

(c) To address challenges introduced in theses (1-5) by designing (1) features with key functions and (2) summarizing guiding aspects of user interface (UI) design for the concept of Moiré Imaging Tool for Scoliosis (MITS) as a proposed research framework for generating, processing and evaluating MIs of scoliotic spines.

Method: (1) Features and key functions are defined based on image processing and image evaluating problems of MIs of scoliotic patients. Selection of segmenting functions (i.e. its filtering and morphological operations) for MITS is based on resulting observations and conclusions as aim (d) is realised. (2) The summary of guiding aspects for designing UI and arrangement of MITS follows functional and comfort considerations, focusing on a simple and user-friendly solution as proposed by WIKLUND [2].

(d) To develop segmenting algorithms based on morphological operations for delineating MFs of scoliotic spines in MATLAB® environment.

Method: Applying various morphological operations with static and adaptive function parameters based on exploratory sequences and observations on 11 MIs created by digital (projection) moiré and XOR logic[1], made available by SALUS Ortopédtechnika Kft.[2]

(e) To conduct a SWOT analysis on MITS and MM used in scoliosis for exploring their viability for medical research

Method: Summarizing strengths, weaknesses, opportunities and threats of the MITS concept and MM applied in scoliosis in scientific, financial and technical aspects.

(f) To lay down solid foundations of a startup for full development and release of MITS after the PhD graduation by implementing aims (a-e)

Method: see methods at aims (a-e).

Fig. 1 shows the content of the dissertation in the context of aims (a-f).

The literature references in this thesis booklet only cover works relevant to the research methods. I refer to the relevant literature in my dissertation, of course, following the reference standards.

[1] In image processing, the logical operation XOR (exclusive OR) is suitable for highlighting the difference between two images or image segments. The XOR logical relationship is true if the values of the pixels in the two input images are different. By displaying differences and contrasts, this principle is particularly suitable for generating moiré images, if the two input images contain a base grid (reference) and its distorted state projected onto a surface.

[2] SALUS Ortopédtechnika Kft. is a Hungarian manufacturer and distributor of medical devices.

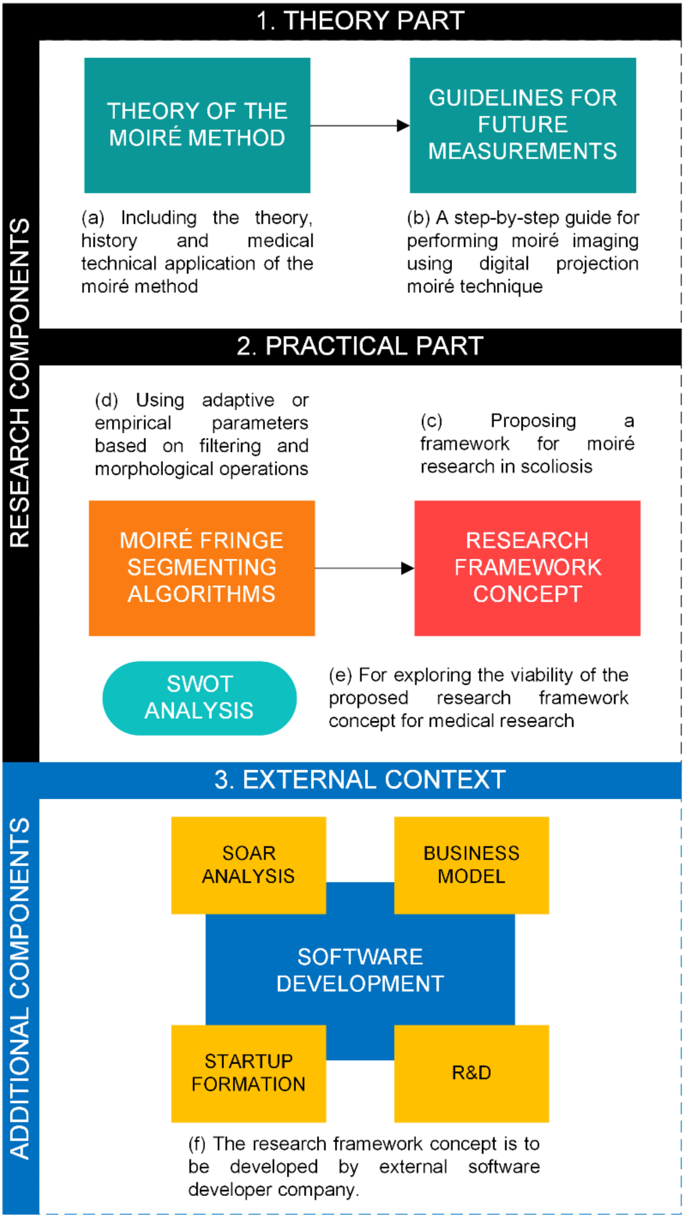

Fig. 1: The content of the dissertation in the context of aims (a-f)

III. Theses

This research follows a deficit-based but solution-focused approach—ie. it aims to provide solution-oriented answers based on gaps and challenging conditions identified in moiré research in scoliosis. In establishing my theses, I aimed for a simple and consistent conclusion in the light of the identified gaps in research and research hindering factors.

Thesis 1

The MM and its medical technical research, being an interdisciplinary field, typically require the expertise of several professions and disciplines including (biomedical) engineers, doctors and other health professionals such as physiotherapists and corset makers, ideally. In these research, the metrological implementation of the MM is tied to engineering design that includes instrument setup and calibration, execution of measurements, error correction and image processing. As the work of medical personnel highly depends on the engineering work that provides the technical conditions of MT, incomplete work organization and communication between engineers and medical professionals may lead to inaccurate calibrations, incorrect analysis of moiré patterns, and thus untapped potential of moiré research—as we can already read in early reports from the 1980s.

Multifunctional (i.e. multidisciplinary and interdisciplinary) workgroups covering both health and engineering disciplines, however, are not always available, and the complex knowledge required for imaging, image processing and image analysis becomes difficult to obtain. Although the concept of interdisciplinarity is frequently used as a magic word, it is something to be learned and acquired. That means that inter- and, also, transdisciplinary processes need to be continuously challenged and questioned—especially with regard to unavoidable frictional losses that derive from translation between disciplines, languages and cultures. This circumstance induced another research in which the author of this dissertation attempted to create a model of an ideal collaborative prototyping environment tailored to a wide variety of disciplines, including medicine and engineering. This work is published as a separate book [3]. On the other hand, reevaluating and, where possible, replacing the need for direct interdisciplinary interactions can also be an efficiency-enhancing solution for work organization—for example, by using automated software workflows.

By partial or complete replacement of the engineering presence in moiré research, the dependence of the medical team on direct engineering work may be significantly reduced and, thereby, the scope for independent work and the efficiency of the team may be increased. Table 1 summarizes the main tasks of engineering in moiré research.

Table 1: Main tasks of engineering in moiré research

MAIN TASKS OF ENGINEERING IN MOIRÉ RESEARCH	
Task	Required expertise
Moiré equipment	
Design	technical
Calibration	technical
Operation	technical / procedural
Maintenance	technical
Measurement	
Image capture *in cooperation with the medical staff*	technical
Moiré production	technical / software
Optimization	procedural / technical
Image processing	
Segmenting moiré fringes	software
Image evaluation	medical-methodological / software
Optimization	procedural / software

To replace functions of the engineering work in moiré imaging, image processing and image evaluation, my first thesis emphasizes the need and potential of a software-based solution:

Thesis 1

> **Medical work using the moiré measurement technique can be significantly decoupled from the engineering presence by using a user-friendly software environment adapted to moiré research, covering imaging, image processing, and image evaluation functions.**

Theses 2-4

The MT is a sensitive method that depends on the position of the subject to be examined—ideally, a position that conforms to a certain measurement standard. In surface topographic examinations of the spine, however, we cannot speak about a generally accepted standardized posture and measurement parameters. Therefore, although MT provides significant pieces of information about the subject, it is a serious drawback that conclusions may easily be drawn with ambiguity.

By this PhD research, only a need for standardisation was identified in the study of scientific literature but not a serious effort to invest. In order to take a rather comprehensive advantage of surface topography in service of patients, additional effort to standardise the MT in spinal examinations is required.

Although the scope of this research does not cover the identification of methods for standardizing MT in scoliosis, it is directed to support efforts aiming at possible recommendations for standardized moiré topographic solutions. The problems of MT caused by the lack of standardization and the challenges in processing and evaluating MIs inspired the idea of a convenient software-based research framework that makes flexible exploratory investigation possible in moiré imaging and fringe analysis.

As a potential benefit of conducting exploratory studies, researchers may be pointed to new directions and ideas to understand existing and/or recognize further research problems at hand. Especially in directing subsequent research, exploratory studies may also be useful for identifying beneficial approaches to research objectives. By recognizing scientific dead ends early, exploratory investigations also have the potential to save time, costs and unnecessary repetitions. Performing this type of research, however, has also risks by definition, since it is not possible to know in advance if something novel will come out of the whole study—this answer requires a certain depth of the research process.

In order to identify software-based research framework solutions adapted to moiré imaging in the diagnostics of scoliosis covering the functions of moiré production, fringe segmentation and fringe analysis, a systematic literature review was carried out on PubMed, Science Direct and IEEE electronic databases. The studies included if they: (1) were related to R&D in MT applied in scoliosis, (2) referred to software-based diagnostics solutions (imaging and evaluation), (3) were published in English, (4) were published in the last 31 years (between January 1990 and 30 April 2022). The literature search yielded 402 articles. Following the full-text review, 1 paper fulfilled the inclusion criteria for further analysis. The number of articles included and excluded at different phases is presented in a PRISMA flowchart (Fig. 2).

The findings with abstracts and the phases of the literature review are written on DVD, as Digital Appendix A and B or can be accessed via *https://bit.ly/3ErXc99* or the QR code below until December 31, 2023.

Based on the literature reviewed—and, also, informal and formal professional consultations conducted during the research period—, it can be stated that there is no recommendation for and implementation of a widely available and operable software-based research environment or its operating model adapted to moiré imaging in scoliosis. Considering this, I formulated my second thesis:

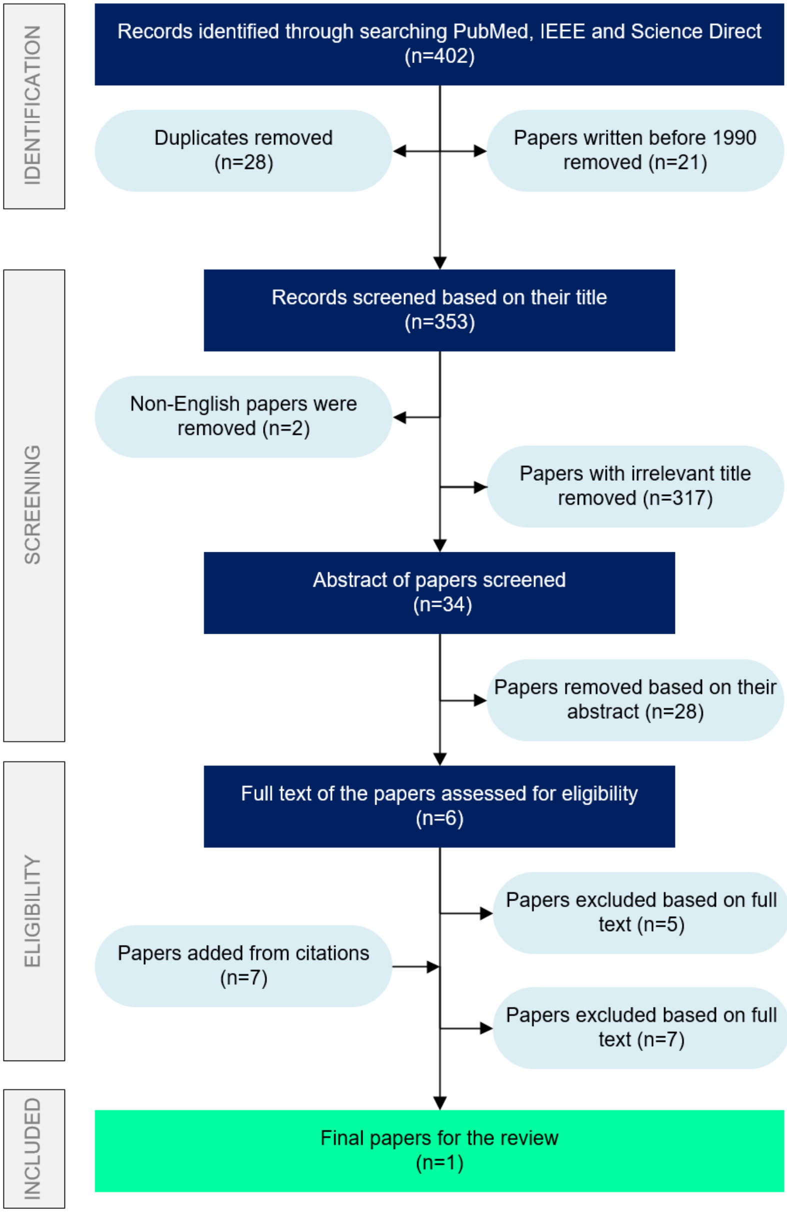

Fig. 2: The PRISMA flowchart of the literature review

Thesis 2

> **Diagnostic research conducted by exploratory mathematical-geometric operations requires a user-friendly software-based research framework covering functions for producing, segmenting and analysing moiré images of scoliotic spine.**

And the information content obtained in an environment conducive to exploratory mathematics-geometric based research by evaluation of MIs taken in different postural states of scoliotic spines, is suitable for comparing and evaluating the reliability of (1) postural settings and (2) parameters applied in various phases of moiré imaging and image analysis. Based on this, my third and fourth theses are:

Thesis 3

> **Using a software environment that allows exploratory mathematics-geometric-based surface topographical studies on moiré fringes of the human spine is suitable for identifying postural optima for the diagnostics of scoliosis via moiré imaging, and, thus, recommending a globally standardizable postural setting.**

Thesis 4

> **Using a software environment that allows exploratory mathematics-geometric-based surface topographical studies on moiré fringes of the human spine is suitable for identifying uniform surface topographic parameters in the diagnostics of scoliosis via moiré imaging, and, thus, recommending globally applicable gold standard parameters.**

Thesis 5

The workload required for segmentation and evaluation of MIs is not inconsiderable; some researchers see the best solution for that in an automatic system. And yet, processing of MIs requires several unique solutions that are especially influenced by optical arrangement, applied illumination, and nature of noise and detection. For reducing uncertainties in moiré pattern analysis, an accurate segmentation of MFs is vital. Precise segmentation serves as a fundamental requirement for the development of mathematical-geometric algorithms to evaluate moiré fringes.

This doctoral study also aims to contribute to the segmenting phase of MI analysis of scoliotic spines by providing algorithmic solutions of filtering and morphological operations. My fifth thesis describes an image processing solution that applies filtering and morphological operations for segmenting digital (projection) MIs generated by XOR logic.

Thesis 5

> **The segmentation of digital projection moiré images produced by XOR logic can be accomplished with an image processing algorithm using adaptive or empirical parameters based on filtering and morphological operations that includes (1) contrast and (2) brightness correction, (3) 2-D Gaussian filter, (4) dilatation, (5) histogram equalization, (6) thresholding, and (7) skeletonization.**

IV. Moiré: Phenomenon, Research and Techniques

In this section, a concise summary of the theoretical and historical background of moiré research, which constitutes an integral part of the dissertation, is provided. While not directly tied to the specific research results, the theoretical and historical perspectives provide essential context and understanding of the evolution of moiré research.

The phenomenon of moiré can be observed if two or more structures with similar geometry (nearly identical arrays of lines or dots) overlap. Then, due to mechanical interferences, a resultant pattern of light and dark fringes appears in the observer's eye (Fig. 3). In general, the dark fringes are called moiré stripes.

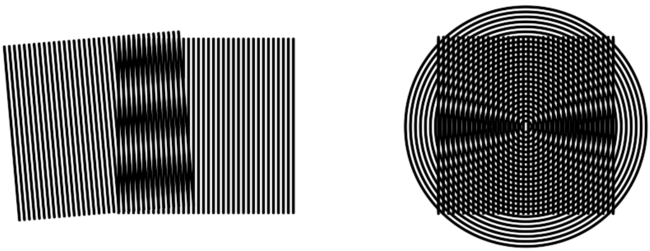

Fig. 3: Moiré patterns of geometric shapes

MFs were elevated to scientific status, first, by LORD RAYLEIGH dealing with diffraction gratings[3] in 1874. concluded that moiré might be made useful for measurement purposes.

In addition to Rayleigh, several researchers, such as FOUCAULT, RIGHI, RONCHI, RAMAN, and DATTA, dealt with the moiré phenomenon but until the middle of the 19th century, the metrological benefits of their observations did not enjoy the scientific attention that they deserved. This was because several problems were encountered in the reproduction of satisfactory gratings required for the production of moiré patterns and in the application of (test) methods. In

[3] The diffraction grating is a collection of periodic light reflecting or transmitting optical elements that split light into rays and scatter it in different directions. The fundamental physical characteristic of a diffraction grating is the spatial modulation of the refractive index.

the 1950s, the problem of producing quality gratings for metrological application at a moderate cost was resolved by a novel principle introduced by SIR THOMAS MERTON.

After this, a significant boost in moiré research, followed by new fields of application, occurred. The development and spread of computer technology had another substantial effect on the increase in moiré research and related publications.

In the 1970s, beyond industrial applications, further research proposed the MT for measurement of the human body.

From the 1980s till present, body surface analysis can be performed from the soles of the feet to the mapping of the legs, the trunk, the spine and the oral cavity. The list of applications can be continued by revealing changes in bones and teeth and the skeletal system. Even by lining up the analysis of facial profile, nasal symmetry and forensic dental samples (sex identification) do not provide a complete picture on the potentials of the moiré technique.

The Shadow and Projection Moiré Techniques

Moiré techniques are stereometric methods of 3D analysis of an object from a 2D image. They differ in regards to the different ways the moiré patterns are created and processed in the topographical analysis. MT is a simple method that requires only a light source, a grid, a camera (detector) and a computer.

The concept of measurement technical application of the moiré phenomenon is based on the idea that while one of the base structures is associated with the surface characteristics (projection grating), the other is used as a reference for the measured object (reference grating). From the resultant moiré pattern of these two structures we can conclude the deviation between the two states of the object examined.

Moiré effect can be produced by several techniques, in the scientific literature, the shadow and projection moiré techniques (SMT and PMT) seem to be the two primary methods of MT used for measurement of the human body.

SMT (Fig. 4) uses a single physical grid and its own shadow projected onto the examined surface to generate interference and moiré pattern.

The PMT (Fig. 5-6) uses two gratings with the same properties: one for projection and another for reference required for detecting moiré patterns.

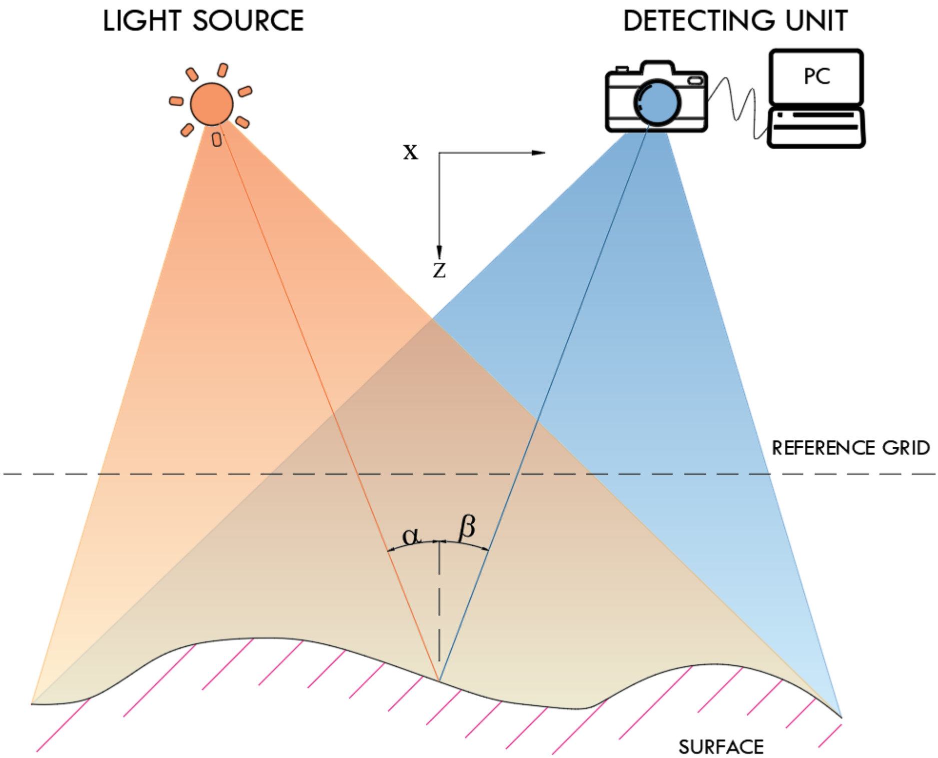

Fig. 4: Optical arrangement of the shadow moiré technique

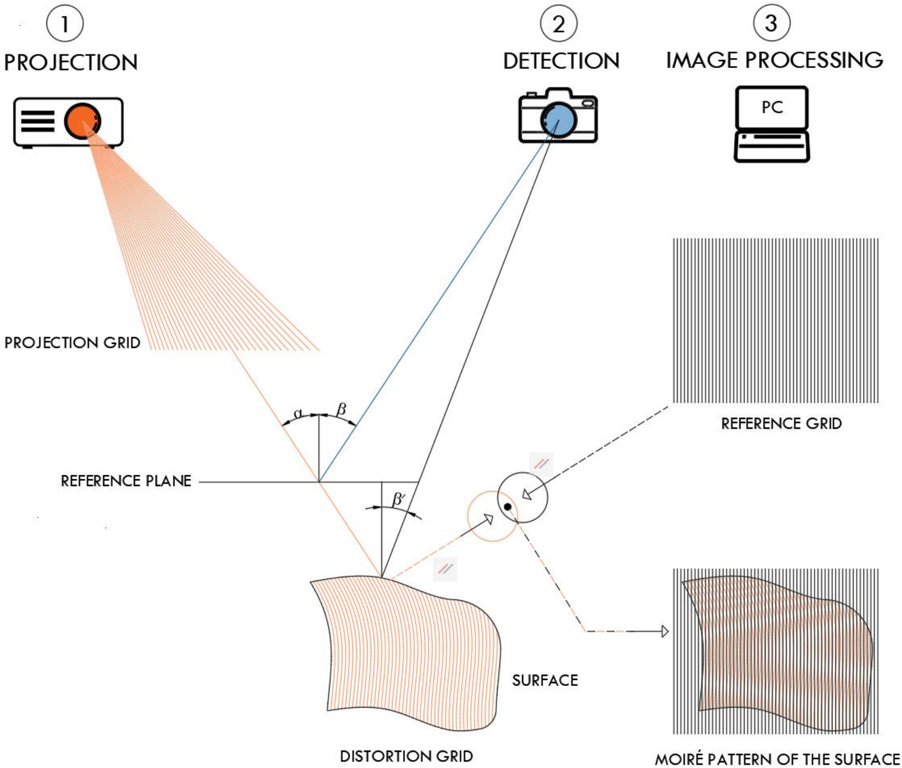

Fig. 5: Optical arrangement of projection moiré technique .

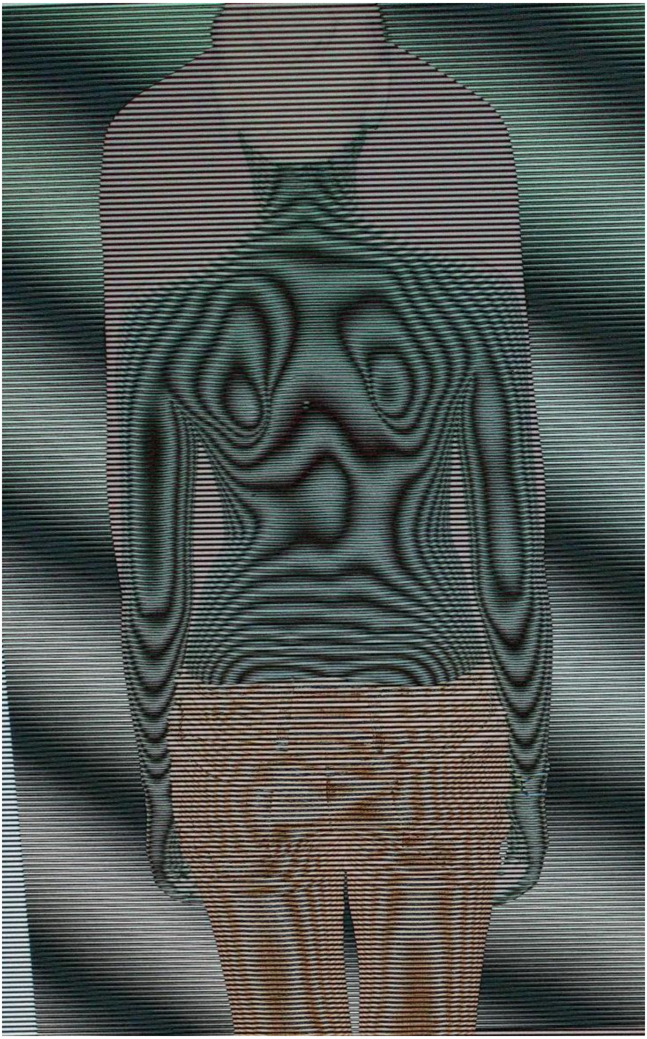

Fig. 6: Moiré patterns of the human back by digital projection moiré technique

Considerations on Moiré Topography in Relation to the Diagnostics of Scoliosis

In relation to diagnostics of scoliosis, the significant advantages of the MM are that it is fast, non-invasive, portable, cost-effective, has no harmful radiation, and it does not require highly skilled professionals to be used. The moiré technique makes it possible to study large target groups in a fast, reproducible and cost-effective way. A moiré technique chosen and algorithmized well can be convenient for substitution or as a complement of X-ray images in scoliosis.

The lack of methodological standardisation is, however, a problem that needs to be resolved in the application of MT in scoliosis. Although we know a few body posture protocols applied during moiré examinations, we cannot speak about a concrete methodology that could lead to generally reliable results. A methodological standard could help the better evaluation of MIs of scoliotic patients with distorted trunks where results can be misinterpreted. Therefore, it is a major drawback that the conclusion drawn will not be without ambiguity.

Based on the study of collected literature, only a need for standardisation but not a serious effort to invest can be seen.

The amount of labour required for the evaluation of MIs is also not inconsiderable. Some researchers see the best solution for that in an automatic system. However, due to the complexity of MFs and various optical-geometrical parameters that require unique solutions, implementing a fully automated image analysis and evaluation is challenging.

For the successful development and application of the moiré technique, it is also vital to have unambiguous communication processes within interdisciplinary research groups. There have been cases where the careless use of the moiré technique resulted in false calibrations and interpretations. Long-term aim of this research covers a detailed process description with adequate evaluating algorithm to bring the medical and engineering knowledge closer and encouraging moiré research in medical (orthopaedic) circles. As a basis for this, a process overview is given as a possible way of applying moiré imaging in scoliosis. Illustration and step sketch are based on digital PMT presented by BALLA et al. [1] in generalized and to some extent completed form—especially by adding additional steps 1, 7, 8 and 9 (Fig. 7).

Ensuring the conditions for successful cooperation though, is a fundamental task of any interdisciplinary research team, but smart, practical and convenient software-based solutions may significantly reduce interdependencies between disciplines, and thereby, increase the efficiency of research.

To address the problems above, a user-friendly system, where image processing challenges can be handled and diagnostic methodologies can be flexibly tested, may be suitable.

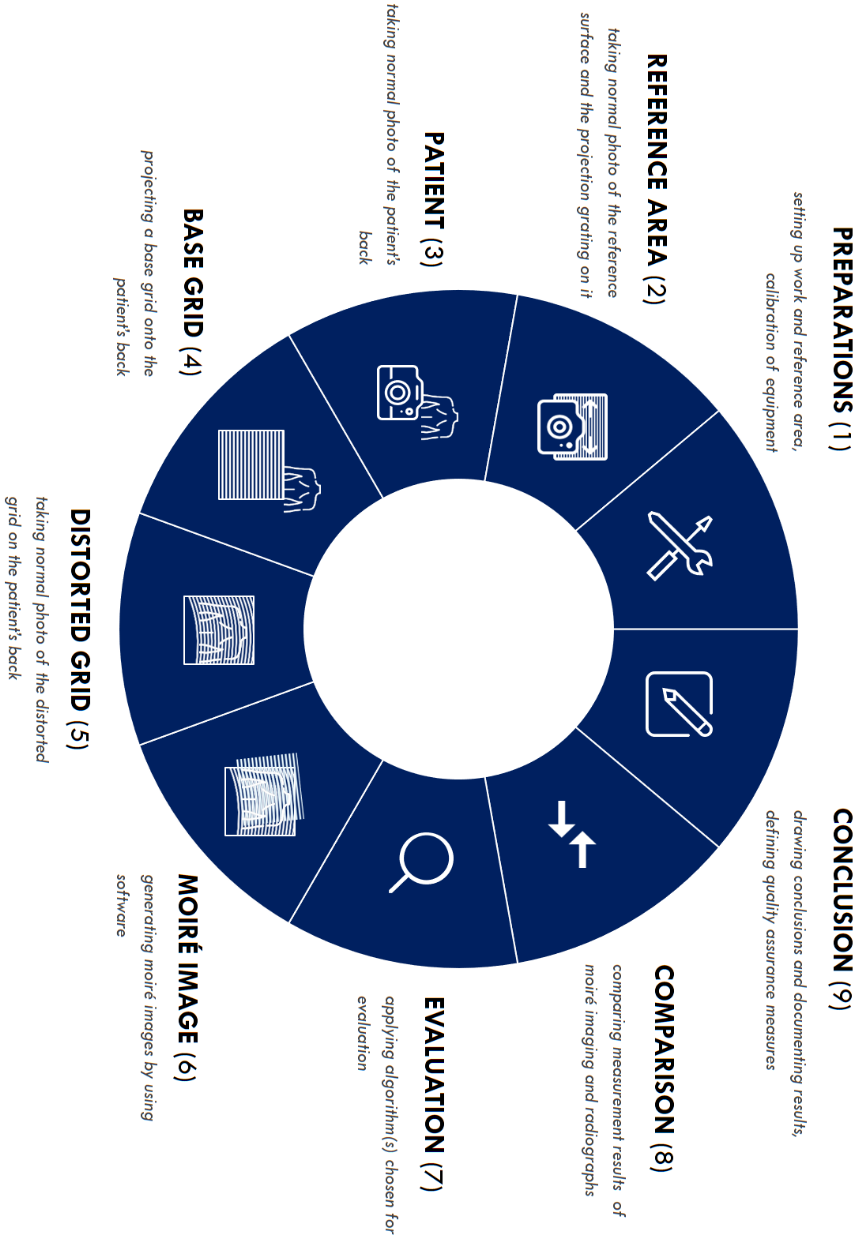

Fig. 7: Process of digital moiré imaging and examination

V. Results and Discussion

In order to present the research results and their analysis in a comprehensive and structured manner, two subsections are utilized. Sec. 5.1 outlines the concept of the proposed software-based research framework, while section 5.2 introduces and critically evaluates the performance and efficiency of the segmentation algorithms. By integrating results with discussion, the aim is to facilitate the interpretation of the relevance of the findings.

A Research Framework Concept for Moiré Imaging in Scoliosis

Disadvantages of MM, such as the high amount of labour intensity in evaluating procedures and possible ambiguous conclusions in determination of spinal curvature angle values, require valid solutions. An automatic system is considered as a solution in compensating labour intensity—especially for examinations of large patient populations in short periods of time. Nevertheless, even with automatic detection of moiré stripes, problems like ambiguous fringe patterns and non-continuous fringes remain existing. For reducing uncertainties in moiré pattern analysis, an accurate segmentation of MFs is needed.

Keeping in mind the circumstances described above, the concept and idea of the Moiré Imaging Tool for Scoliosis (MITS) was proposed by the author as an aswer to Theses 2-4. The concept of MITS is introduced as a software-based research framework for producing, processing and evaluating MIs of scoliotic spines based on manual and semi-automated solutions in a user-friendly environment. The intent behind the concept is to stimulate practice- and exploratory-based moiré research in scoliosis by both medical and biomedical professionals—in such a manner that it aims to find workable and realistic answers to image processing and evaluating challenges.

Specific aims of MITS with respect to generating, processing and analysing MIs of scoliotic spines are as follows (1-3):

(I) **To segment MFs in quasi-real-time** (QRT) by applying manual adjustable morphological operations and built-in algorithms to support moiré pattern evaluation—**Fringe Segmentation Tool** (FST, Fig. 8).

For practical illustration of the fringe segmenting function of the MITS concept, an application is developed in MATLAB environment (Fig. 9). The prototype application for fringe segmentation allows a dynamically changeable and user-friendly processing configuration on MIs created with XOR logic. The prototype was developed in MATLAB App Designer and provides filtering and morphological operations for segmentation of MFs by applying (1) brightness and (2) contrast enhancement, (3) 2-D Gaussian filter, (4) thresholding, (5) histogram equalization, (6) inversion and (7) skeletonization. By using the prototype, a relatively accurate manual and automatic segmentation can be performed in QRT with visually traceable results that may even be used for specific measurements.

Filtering and morphological operations built into the application, although they make adaptive and flexible segmenting process possible, can lead to data loss, and thereby to sporadic segmentation. An improved solution to the software could replace time demanding and complex segmentation methods. A possible way of improving the fringe segmenting application is to extend its functions with further image processing operations such as (1) dilation for gradually enlarging the boundaries of regions of foreground pixels, (2) high-pass filters for image sharpening, (3) adaptive thresholding with local mean and global mean values, (4) bit-wise XOR for values of low contrasted and over contrasted copies of images, (5) fuzzy inference system for combining the manual and pre-defined automatic algorithms, and (6) deep learning algorithms for automatic segmenting procedures (a high amount of sample data required).

The operation of the prototype of the FST is demonstrated in Digital Appendix C on the DVD or can be accessed via https://bit.ly/3ErXc99 or the QR code below until December 31, 2023.

(II) **To analyse segmented moiré contour lines** and their mathematical-geometric relations to identify methods for calculating spinal curvature angle values approximated to Cobb angles—**Contour Analysis Tool** (CAT, Fig. 10).

The key elements of CAT are (1) measuring functions os MFs such as calculation of area, circumference, angles and largest asymmetries (e.g. compared to the midline of the back), (2) button bar for automated calculations (Fig. 10 exemplifies this with Kamal's algorithm[4]), (3) panel for image and image object selection, (4) Cobb angle calculator, and (5) standard buttons for loading, unloading, exporting images, resetting parameters, and closing the application.

(III) **To support moiré pattern production** on input images containing projection grid only produced by digital projection moiré technique—**Moiré Production Tool** (MPT, Fig. 11).

The concept of MPT is to support research applying digital PMT in scoliotic cases by providing customizable overlaying geometries for generating moiré patterns on input images containing projection grid only. The key elements of MPT are (1) selectable geometries and their transformation options, (2) panel for image and overlaying geometry, and (3) standard buttons.

The implementation of MITS with all of its planned features and functions is to be carried out in cooperation with a software developer company. The final functions of the proposed research framework will be designed based on collected end-user (i.e. physicians and (bio)medical professionals) feedbacks in the beta release of the software.

Healthcare and medical research related information and data can be complex to understand and communicate. User interfaces (UIs) often have superficial design problems that have negative effects on product usability and appeal. The UI concept of MITS is in the preparation phase. The ultimate goal of UI development for MITS is to create a well-structured, transparent and user-friendly software environment that clearly visualizes information and actions available to and triggered by the user.

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[4] Kamal's method uses correlations between points describing the symmetry or asymmetry of the back to determine the curvature angle of the spine on MIs.

Based on practical suggestions for medical device interfaces and healthcare applications, the following guiding aspects are proposed in developing UI design for MITS: (1) reducing screen density, (2) providing navigation cues and options, (3) ascribing to a grid, (4) creating visual balance, (5) limiting the number of colors, (6) simplifying typography, (7) using hierarchical labels, (8) Using simple language, (9) refining and harmonizing icons, (10) eliminating inconsistencies, (11) following common best-practice standards.

Although the exact business model for MITS is under development, the concept is meant to be released as an inexpensive and widely accessible tool with low system requirements. In order to summarize the viability of the MM and MITS for medical research, a SWOT analysis is also conducted in scientific, financial, and technical aspects (Table 2-5).

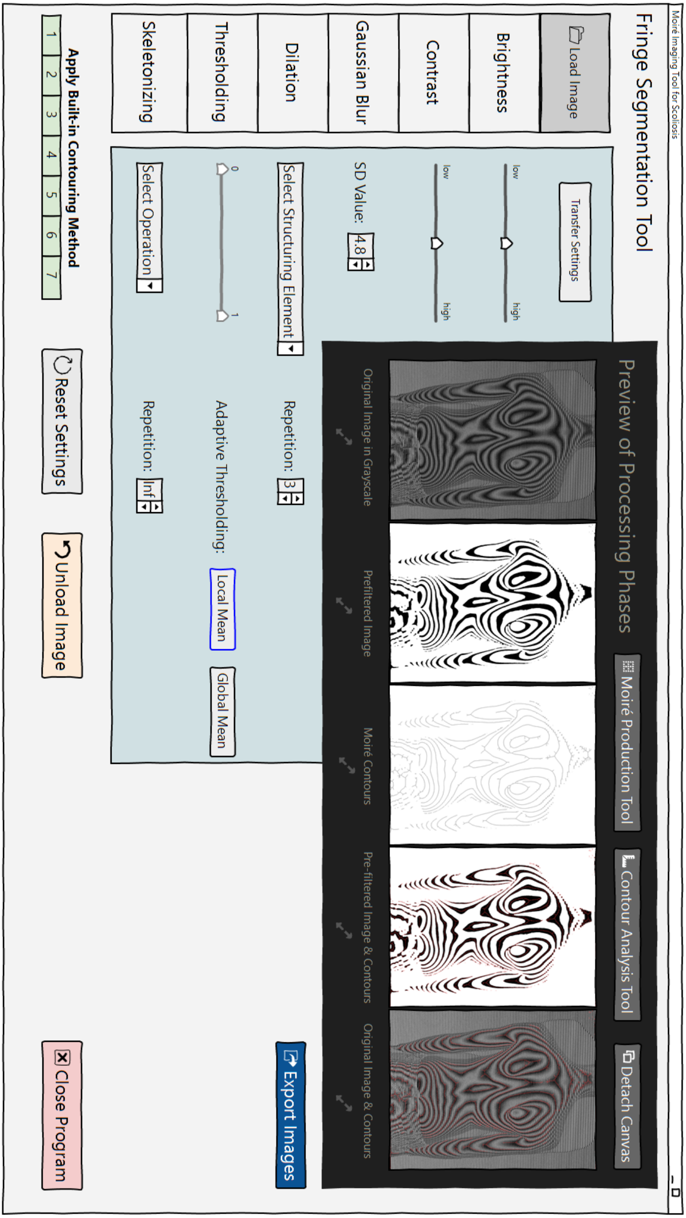

Fig. 8: Concept preview of Fringe Segmentation Tool.

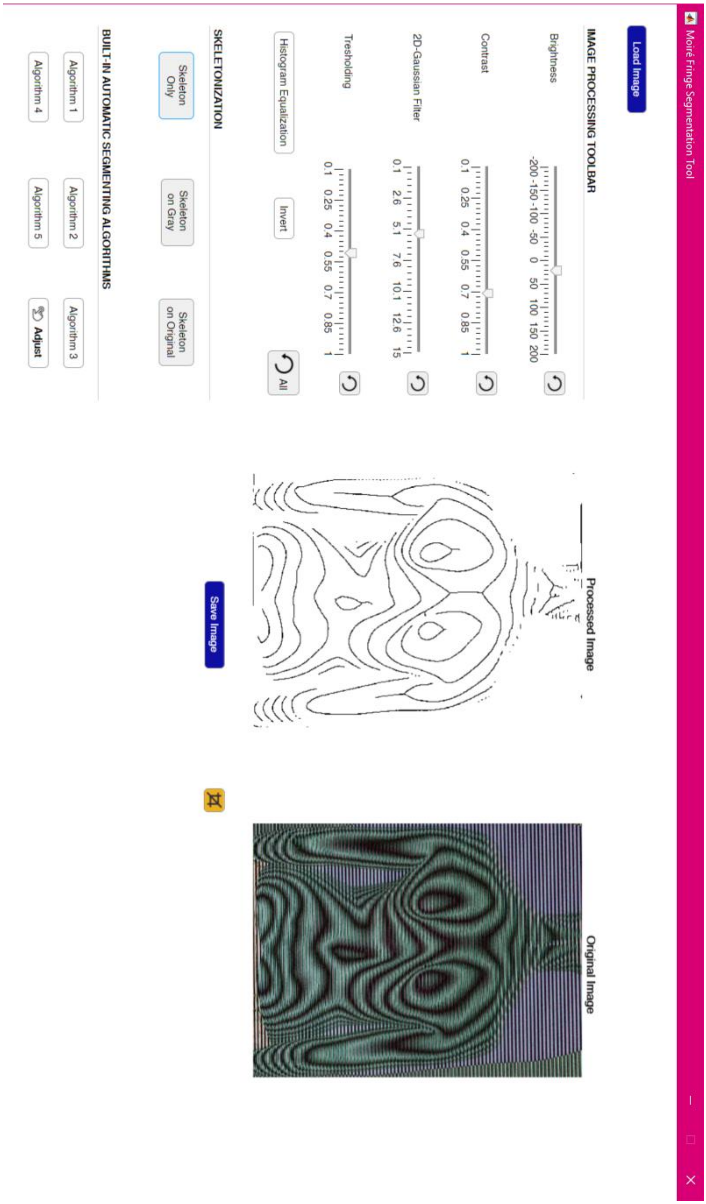

Fig. 9: The main screen of the prototype of the Fringe Segmenting Tool

Fig. 10: Concept preview of Contour Analysis Tool

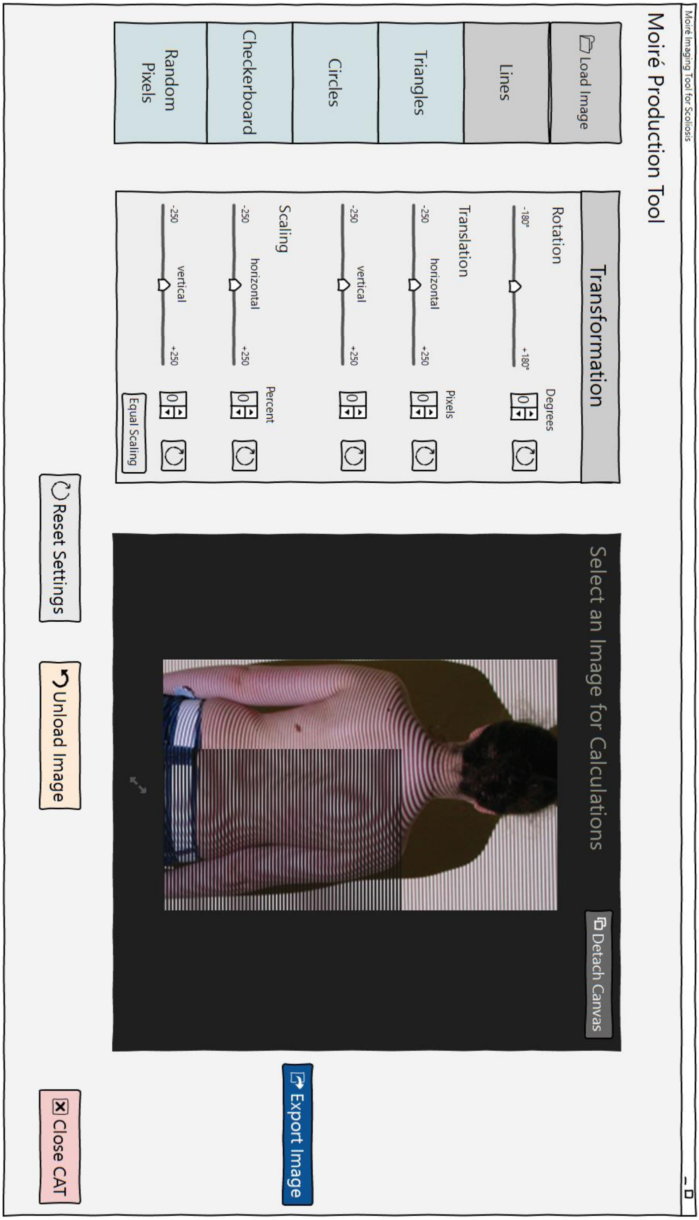

Fig. 11: Concept preview of Moiré Production Tool

Table 2: SWOT analysis of MITS: strengths

STRENGTHS		
Moiré method		
▪ The method is simple and fast to operate ▪ Fast data acquisition in quasi-real-time ▪ Flexibility: both static and dynamic events can be studied ▪ Repeatability ▪ Easy availability of equipment ▪ No pressure exerted on the body ▪ Non-invasive, non-ionizing examinations: may violate neither political, religious and other beliefs nor ethical issues ▪ Portable equipment ▪ Low-cost equipment (pc, projector, camera)		
Moiré Imaging Tool for Scoliosis (MITS)		
▪ Adaptable parameters, variable resolution ▪ (Quasi-)real-time experimental research becomes possible by FST, CAT, MPT ▪ Multifunctionality (3 in 1) ▪ Supporting automatic algorithms (fringe segmenting and evaluation) ▪ No special training required ▪ Possible accelerator role in defining standardized body posture ▪ Low system requirements of the software (pc and storage) ▪ Low-cost (software and equipment) ▪ Location- and time-independent ▪ Fast operation reduces working hours		
SCIENTIFIC ASPECTS	TECHNICAL ASPECTS	FINANCIAL ASPECTS

Table 3: SWOT analysis of MITS: weaknesses

WEAKNESSES		
Moiré method		
▪ Lack of standard in body posture may lead to false or inconsequent results ▪ Moiré topography is sensitive to layout and geometry ▪ Thorough surface analysis requires very serious considerations and post-processing ▪ Increased resolution may encounter technological limitations, or can only be achieved at the expense of other metrologically relevant features ▪ Achievement of high contrast is challenging ▪ Examination of high-slope surfaces is problematic		
Moiré Imaging Tool for Scoliosis (MITS)		
▪ Lack of reliable algorithms for evaluation ▪ Accurate segmentation of moiré stripes is problematic ▪ Thorough surface analysis requires serious post-processing		
SCIENTIFIC ASPECTS	TECHNICAL ASPECTS	-

Table 4: SWOT analysis of MITS: threats

THREATS		
Moiré method		
▪ Only a need for a standardised body posture but not a serious effort to invest can be identified ▪ Communication problems may lead to miss-calibrations of the moiré equipment ▪ Collaboration tools and methods are not known or used appropriate in the research group ▪ Geographical distances may cause logistic and communication issues ▪ Insufficient manual/instructions for use of method ▪ Investors and financial support for research may be challenging to find ▪ Financial resources for tenders and investors may not be available in time		
Moiré Imaging Tool for Scoliosis (MITS)		
▪ No extensive testing before release ▪ Target audience is not reached ▪ Insufficient or incomplete implementation (complicated use, user-unfriendliness, slow operation etc.) ▪ Insufficient manual/instructions for use of method and software ▪ Data protection issues		
SCIENTIFIC ASPECTS	TECHNICAL ASPECTS	FINANCIAL ASPECTS

Table 5: SWOT analysis of MITS: opportunities

OPPORTUNITIES		
Moiré method		
▪ Substitution or as a complement of X-ray images		
Moiré Imaging Tool for Scoliosis (MITS)		
▪ Experimental research carries scientific and innovation potential—e.g. standard body posture protocols may be identified by using the software ▪ Improved or newly developed evaluating algorithms by building digital databases from the results (big data, machine learning)		
Moiré method and MITS		
▪ Method and software can be used anywhere in the world, since it does not depend on local technologies		
SCIENTIFIC ASPECTS	TECHNICAL ASPECTS	FINANCIAL ASPECTS

Citizen Science as a Tool for Improving the Concept of Moiré Imaging Tool for Scoliosis

The proposed concept is meant to be a tool for moiré research adapted to scoliosis, so its potential users are primarily medical and biomedical professionals who can provide useful input for R&D. An effective and innovative way of improving the concept is the inclusion of the citizen science (CS) methodology. The essence of CS is that people without specialized scientific background carry out data collection in support of scientific projects, typically with the orientation of institutions intrested in R&D. In recent decades, CS has gained the legitimacy of the scientific community as a data collection methodology, and it also provided valid results in the field of medicine.

In the case of MITS, the target population of citizens is expected to be made up of those interested in locomotor diseases (trainers, nurses, school health professionals) and people affected by spinal deformities. On the other hand, citizens who are interested in IT and have above average ICT competencies with 'willing to experiment' attitude can be involved in the fine-tuning of the proposed manual MF segmentation process.

An analytical system that is embedded in a beta release can easily collect user data that provides valuable contribution to the future development of the software.

As part of a separate research, the author also developed a CS mentoring program that proposes a framework for involving and supporting committed citizens in scientific research [4].

The long-term goal is for MITS to become capable of collecting and utilizing analytical data of independent discoveries of millions of citizens for development of spinal diagnostic solutions.

Segmenting Moiré Fringes of Scoliotic Spines

For reducing uncertainties in moiré pattern analysis, an accurate segmentation of MFs is vital. In this study, two algorithms, a static and an adaptive one, were provided for segmenting MFs of the spine in MATLAB® environment. The algorithms use an empirically established sequence of filtering and morphological operations performed on 11 MIs obtained from SALUS Ortopédtechnika Kft. Original MIs were software-generated applying digital PMT by XOR logic.

The initial phase of research introduces the algorithmic sequence of filtering and morphological operations with static function parameters. The applicability of the algorithm is confirmed by a simple, fast to process and, for the most part of sample images, accurate MF segmentation. The results indicated that the static algorithm constitutes a suitable base for further research on segmenting MFs with adaptive and dynamic function parameters and adaptive image processing solutions, and replacing time demanding and complex image processing techniques.

The fully automated adaptive segmenting solution was introduced based on the static algorithm. Similar to the results of the static algorithm, the applicability of the adaptive method is also confirmed by a simple and, for the most part of sample images, accurate MF segmentation.

In terms of general usability, despite the fast execution speed of the static algorithm, the necessity of manual re-adjusting static function parameters is a challenging and—especially in higher patient populations—time-consuming process. To get similar results on MIs other than the 11 sample images applied in this study, function parameters need to be manually/empirically determined and implemented in the code. Therefore, static function parameters became desired to be improved by automatic parameterization. This had been fulfilled by adaptive function parameters. The adaptive algorithm, while successfully eliminates the need for manual re-adjustment of parameters, its execution speed at applying 2-D Gaussian filter based on root mean square (RMS) values remains to be optimized.

Fig. 12-19 show 3 examples of the 11 static and adaptive segmented MIs side-by-side on the grayscale (Fig. 12, 14, 16, 18) and superimposed on the original image (Fig. 13, 15, 17, 19). In Table 6 and 7, the time courses of the static and adaptive algorithms are summarized in average elapsed and processing time. A summary of the steps of both algorithms is given in Table 8.

In both solutions, the segmenting algorithm leads to a partial or sporadic segmentation of moiré stripes. Image details (i.e. parts of moiré stripes) and segmenting accuracy are lost mainly due to original fringe quality and characteristics such as (a) pale—mostly around the shoulders and the waist—, (b) convergent, (c) wider/blurred MFs, (d) image noise caused mostly by residual grating, and (e) unwanted branches generated by skeletonizing operation (Fig. 20).

For problems (a-e), a more sensible solution is required. A possible way for further research might be to improve the algorithm with adaptive and dynamic function parameters based on values of low contrasted and over contrasted images in combination with adaptive thresholds. Another possible direction of research is to combine the algorithm with segmentation approaches based on a fuzzy inference system.

Table 6: Time course of the static algorithm

STEPS	PROCESS	AVERAGE TIME [sec]*	
		Elapsed	*Processing*
1	Manual selection of ROI	excl.	excl.
2	Determining object class	0.02567	0.02567
3	Duplicating image for reference	0.02593	0.00026
4	**Converting in grayscale**	**0.02717**	**0.00124**
5	**Enhancing contrast**	**0.03990**	**0.01272**
6	**Increasing brightness**	**0.04036**	**0.00046**
7	**Refining contrast**	**0.04348**	**0.00312**
8	**2-D Gaussian filter**	**0.05781**	**0.01433**
9	**Dilation**	**0.06195**	**0.00414**
10	**Thresholding**	**0.06901**	**0.00705**
11	**Skeletonization**	**0.17165**	**0.10264**
12	Saving images in *.png* files	0.61555	0.44390
13	Visualizing results	0.73376	0.11821

*System used: CPU: Intel® Core™ i5-8300H @ 2.30 GHz, GPU: NVIDIA GeForce GTX 1050 (4 GB VRAM), RAM: 8 GB.

Output images are saved as skeletonized moiré contours (transparent and white-backgrounded) and their overlays on binarized and input images.

Table 7: Time course of the adaptive algorithm

STEPS	PROCESS	AVERAGE TIME [sec]*	
		Elapsed	*Processing*
1	Reading image and grayscale conversion	0.02655	0.02655
2	**Contrast enhancement**	**0.08345**	**0.05690**
3	**2D-Gaussian filter** [based on RMS]	**390.76934**	**390.68588**
4	**Histogram equalization**	**390.78183**	**0.01249**
5	**2D-Gaussian filter** [based on PSNR]	**390.80406**	**0.02224**
6	**Thresholding**	**390.80862**	**0.00455**
7	**Skeletonizing**	**390.92148**	**0.11286**
8	Saving image	391.23279	0.31131

*System used: CPU: Intel® Core™ i5-8300H @ 2.30 GHz, GPU: NVIDIA GeForce GTX 1050 (4 GB VRAM), RAM: 8 GB.

Output images are saved as skeletonized moiré contours (transparent and white-backgrounded) and their overlays on binarized and input images.

Table 8: Summary of steps in static and adaptive segmenting algorithms

STEPS	STATIC ALGORITHM	ADAPTIVE ALGORITHM
1	**Contrast enhancement** by default value of *imadjust* function	**Contrast enhancement** based on root mean square values
2	**Brightness increase** by predefined values	**2-D Gaussian filter** based on root mean square values
3	**Contrast refinement** by predefined values	**Histogram equalization** by using function *histeq*
4	**2-D Gaussian filter** by predefined standard deviation	**2-D Gaussian filter** based on PSNR
5	**Dilation** applied by predefined values 3x	**Thresholding** applied globally based on Otsu's method
6	**Thresholding** by predefined values	**Skeletonization** by using *bwmorph* function
7	**Skeletonization** by using *bwmorph* function	—

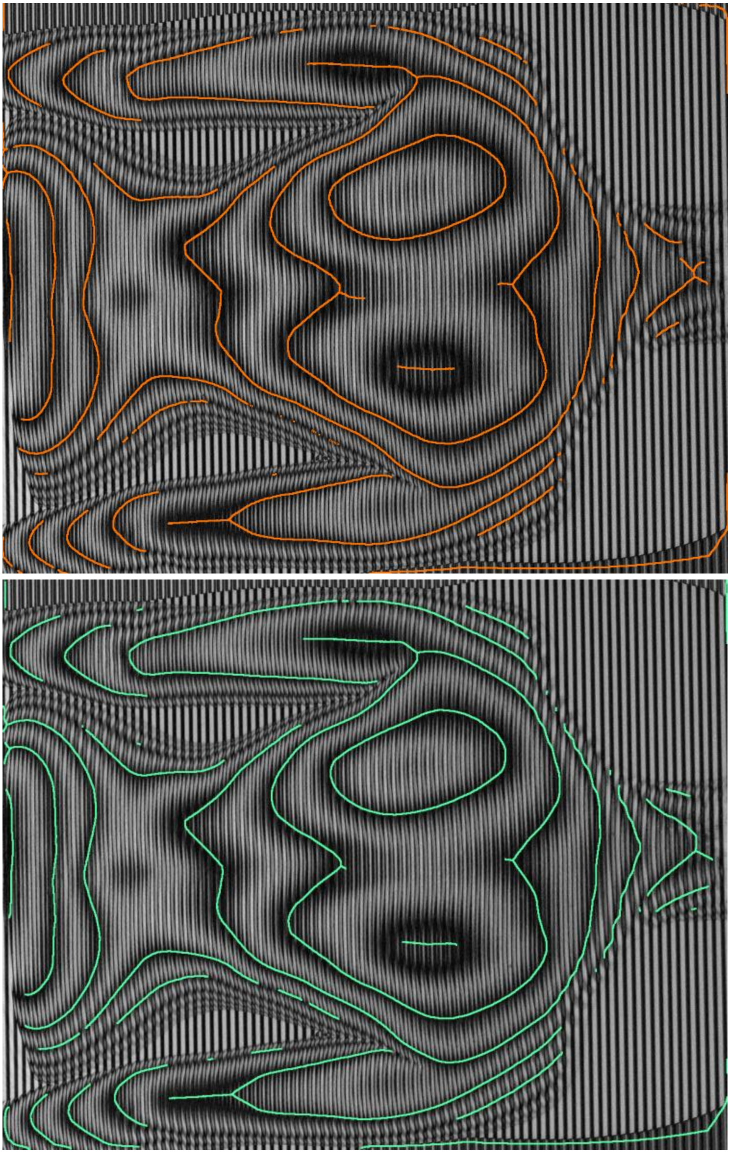

Fig. 12: Static (orange) and adaptive (green) segmented moiré fringes of image no. 1—displayed separately.

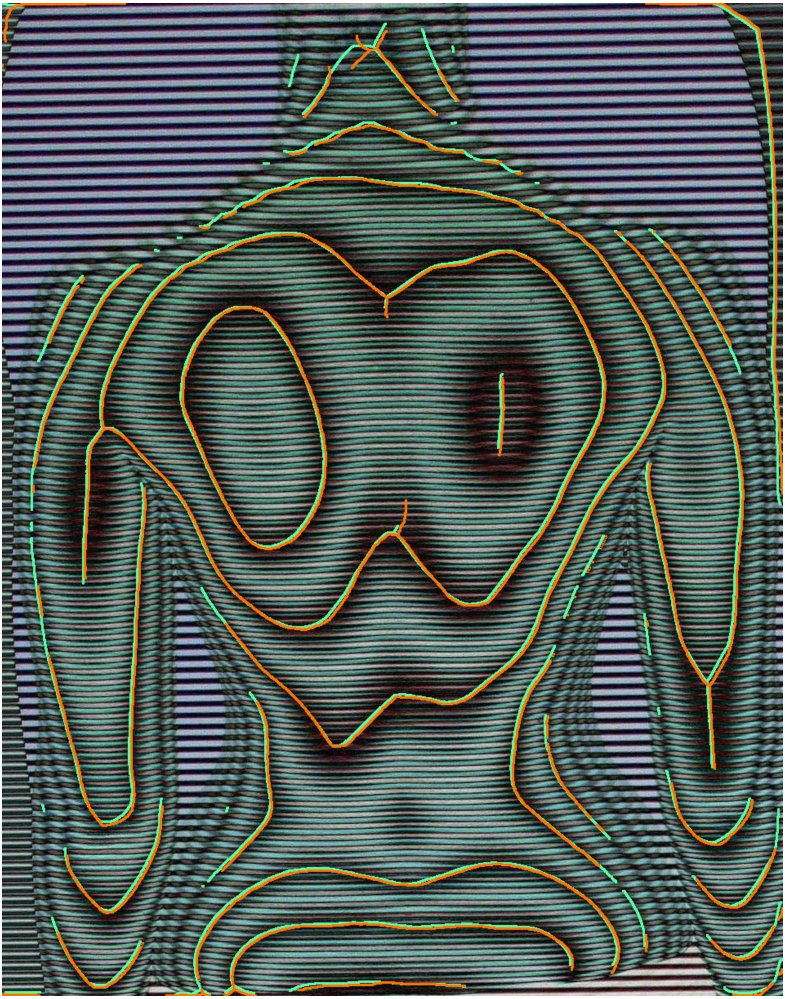

Fig. 13: Static (orange) and adaptive (green) segmented moiré fringes on image no. 1—displayed merged.

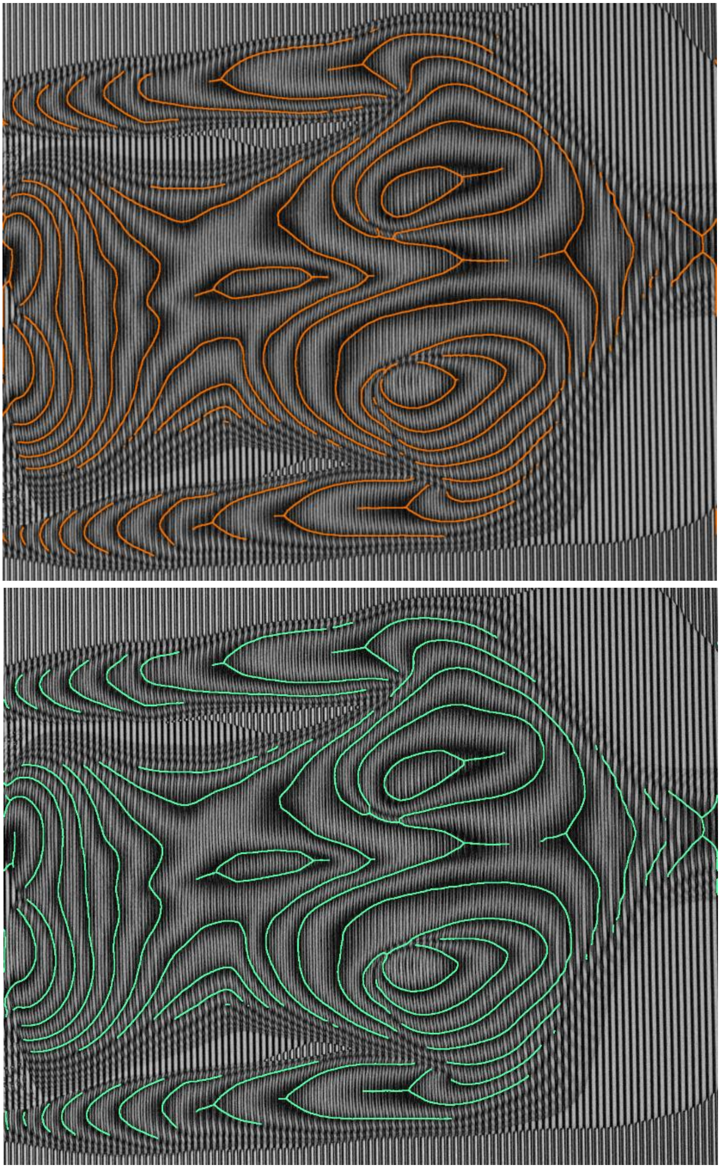

Fig. 14: Static (orange) and adaptive (green) segmented moiré fringes of image no. 2—displayed separately.

Fig. 15: Static (orange) and adaptive (green) segmented moiré fringes on image no. 2—displayed merged.

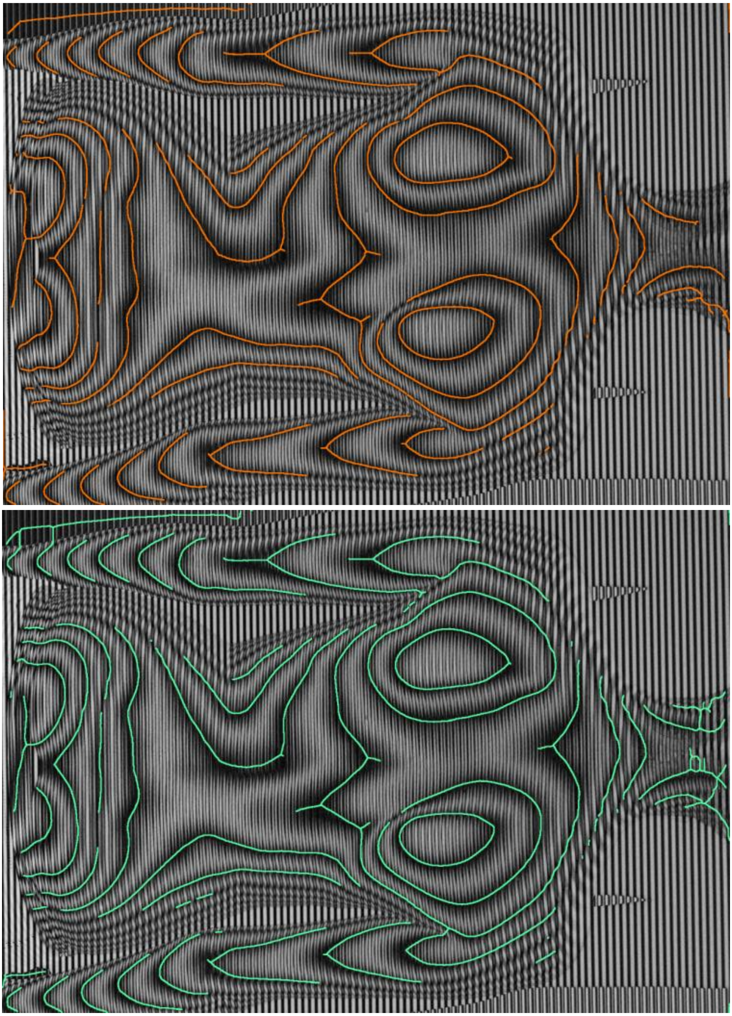

Fig. 16: Static (orange) and adaptive (green) segmented moiré fringes of image no. 3—displayed separately.

Fig. 17: Static (orange) and adaptive (green) segmented moiré fringes on image no. 3—displayed merged.

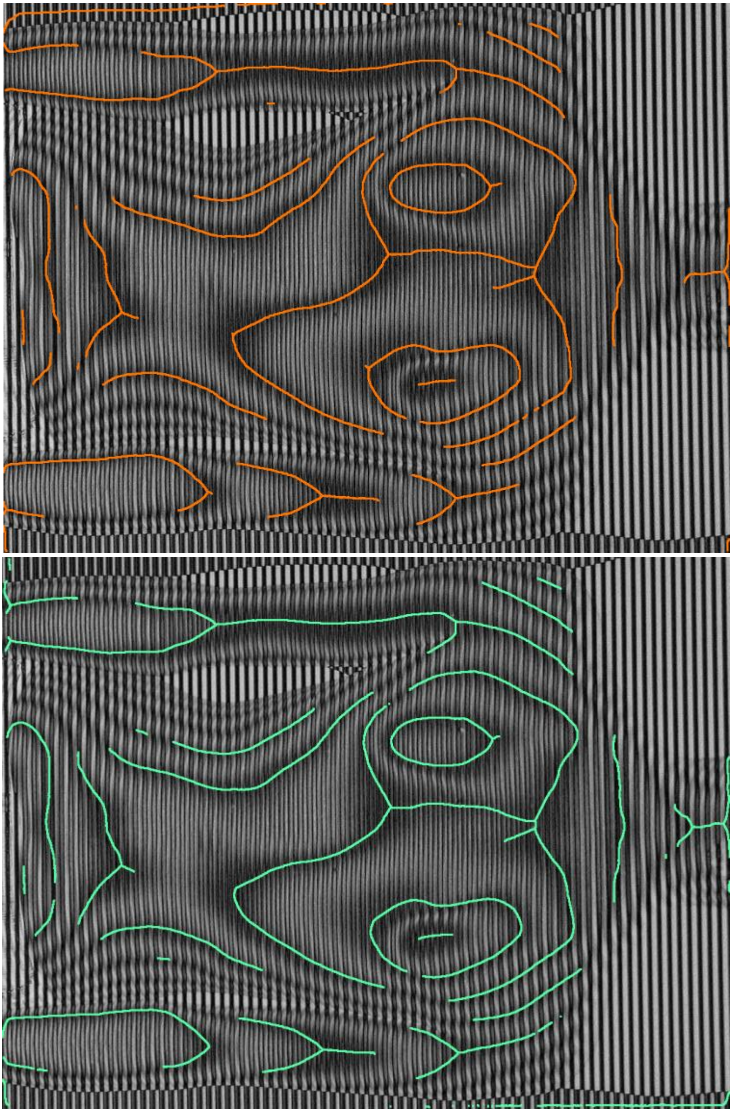

Fig. 18: Static (orange) and adaptive (green) segmented moiré fringes of image no. 4—displayed separately.

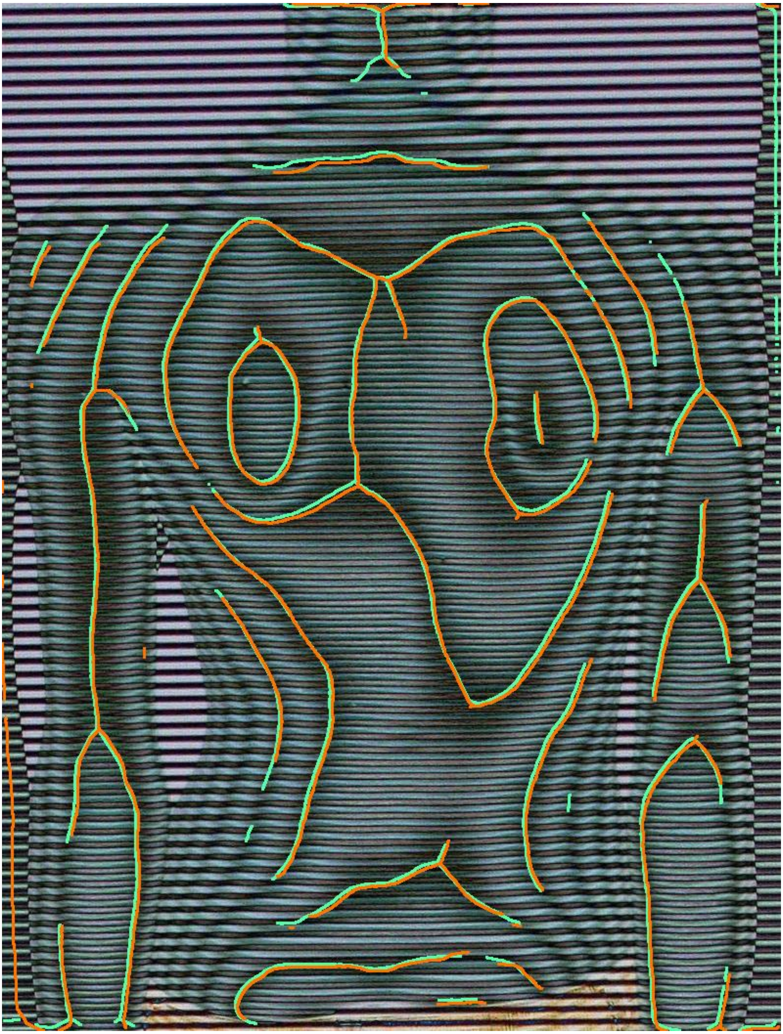

Fig. 19: Static (orange) and adaptive (green) segmented moiré fringes on image no. 4—displayed merged

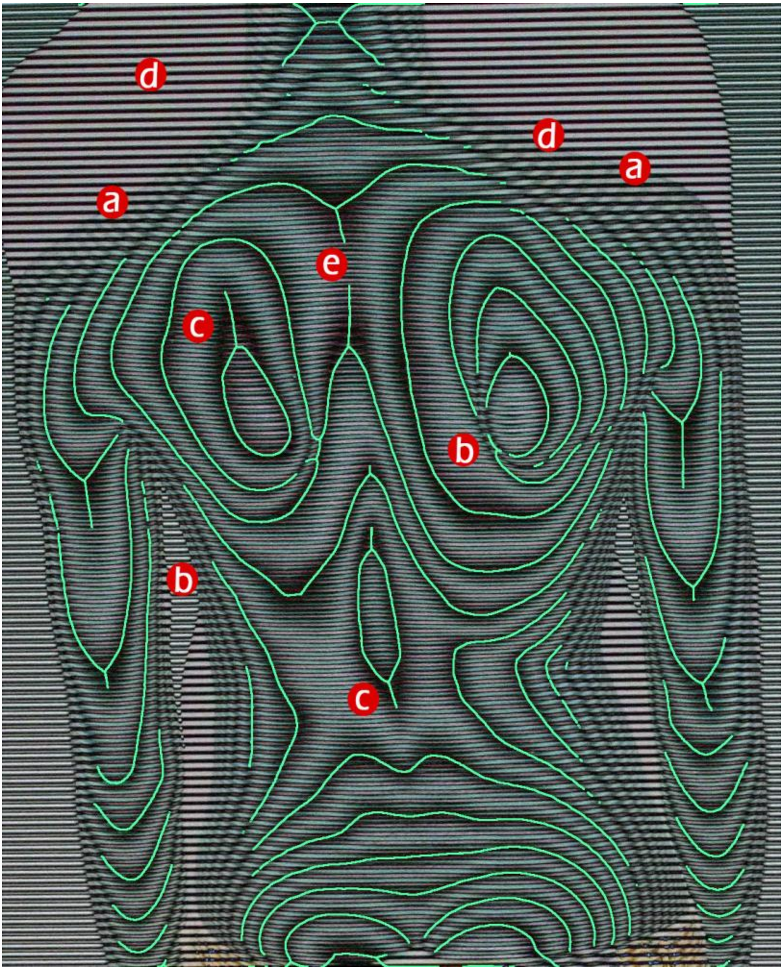

Fig. 20: Problems to be handled in moiré fringe segmenting algorithms

(Illustrated on static segmented MI no. 2)

(a-c) pale, convergent, and wider/blurred moiré fringes

(d) noise of residual grating

(e) unwanted branches

VI. Summary and final thoughts

This dissertation focuses on an interdisciplinary field that belongs to the category of R&D with innovation potential rather than traditional research. The thesis focuses on the concept of a software-based research framework aimed at creating, segmenting and analyzing moiré patterns. Although the nature of the topic of the thesis concerns both medical and technical aspects, its language predominantly reflects the latter perspective, as the author himself is an engineer. Accordingly, in understanding the occasionally complex content of this dissertation, he relies on the reader's openness and receptiveness. The complexity of the topic and the rich potential of R&D are highlighted by the fact that the implementation of the concept presented goes beyond the work of one person, since in order to achieve its goal, i.e. the medical application of moiré-based imaging and analysis, an interdisciplinary team of medical professionals and engineers is needed. The approach required for this is therefore an exciting intersection of medical research and technical development, where the collaboration of experts with medical and engineering background is indispensable to achieve successful results.

Below, I summarize how the targeted challenges were addressed and what results were achieved, as well as the directions I plan to take in advancing the interdisciplinary project.

This research attempted to provide feasible and realistic answers for challenges indicated in Theses 1-5. These challenges include:

(1) The decoupling of engineering presence required for MT in medical work and research (challenge introduced in Thesis 1)

(2) Providing a software-based framework for diagnostic research by producing, segmenting and analysing MIs of scoliotic spine based on exploratory mathematical-geometric operations (challenge introduced in Thesis 2)

(3) Identifying postural optima in moiré imaging based on exploratory mathematical-geometric operations performed on MIs (challenge introduced in Thesis 3)

(4) Identifying uniform surface topographic parameters in moiré imaging based on exploratory mathematical-geometric operations on MIs (challenge introduced in Thesis 4)

(5) Adaptive or empirical segmentation of MIs produced by PMT and XOR logic based on filtering and morphological operations (challenge introduced in Thesis 5)

To address the challenges (1-5), the concept of MITS was proposed as a user-friendly, software-based and exploratory research framework adapted to moiré research in terms of generating, processing and evaluating MIs of scoliotic spines. The proposed concept is meant to be an easy-to-use tool for moiré research in scoliosis with potential users of medical and biomedical professionals.

The concept of the research framework allows medical professionals to independently generate, segment, and evaluate MIs, regardless of location and time, and without the need of severe computing power (challenge 1-2).

The concept of MITS frames exploratory research with mathematical-geometric methods that are suitable for proposing postural optima and / or uniform surface topographic parameters by comparing and evaluating MIs taken in different body postures (challenge 3-4).

In the concept of MITS, exploratory research is provided by flexible image processing and image evaluating operations, the final functions of which will be incorporated into the beta version of the planned software development based on end-user feedback.

The functionality of the segmenting function (FST) of the concept was illustrated with a program developed in MATLAB environment. The segmentation of MIs produced by digital PMT and XOR logic was realized by a sequence of filtering and morphological operations with static and adaptive function parameters (challenge 5). Further R&D can make both algorithmic solutions suitable for replacing time demanding and complex segmentation methods.

On the viability of the MM and MITS for medical research, a SWOT analysis provides scientific, financial and technical levels. In a later stage of the MITS project, a positive and future-oriented SOAR analysis will be conducted to assess the product and its innovation potential based on well-defined KPIs.

Depending on the development possibilities, the MITS concept is also open for the development of an easy-to-use projection moiré equipment in addition to the software product. Thereby, a complete replacement of engineering presence, which is currently a requirement for any medical research that applies MT, can be implemented.

The next phase of the MITS project includes (a) the development of business model and advertising campaign, (b) the development and release a beta version of MITS by a software developer company for collecting practical end-user feedbacks, (c) the improvement and test of the software in accordance with the collected data, and (d) the release of alpha version of MITS.

An effective and innovative way of fine-tuning the software is the inclusion of the citizen science (CS) methodology.

With all this, the aim of the PhD thesis, the preparation of selected work packages of MITS for professional software development, has been successfully realized.

The implementation of MITS, however, can only provide a framework for moiré research. For the success, though, more is needed—the determination of health professionals, their desire to discover and explore and, not least, their persistent professional humility.

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