A Research Framework Concept Adapted to Moiré Imaging in Scoliosis

Doctoral (PhD) Thesis

CSABA BOGDÁN

University of Pécs Medical School
DCHCMPhS
Pécs, 2023

A Research Framework Concept Adapted to Moiré Imaging in Scoliosis

Doctoral (PhD) Thesis

Submitted by:	**Csaba Bogdán**
Neptun-code:	**ORSAKF**
at	**Clinical Studies on Locomotion Programme in Doctoral School for Clinical Medical Sciences**
Head of the Doctoral School:	**Dr. Lajos Bogár**
Programme Leader:	**Dr. Péter Than**
Supervisors:	**Dr. Andor Dániel Magony**
	Dr. Miklós Tunyogi-Csapó

University of Pécs Medical School
DCHCMPhS
Pécs, 2023

DECLARATION OF INTEGRITY

I hereby affirm that this research work was written solely by myself and that I have not previously submitted this work at another educational institution for the purpose of receiving a doctorate degree. In particular, contributions by other persons in this work have been appropriately cited and the data gathered through the methods described have been accurately reproduced.

This PhD dissertation continues, completes and summarises the research started in my bachelor's (Mechatronics Engineering, BSc, 2015-2018, University of Pannonia), and continued in my master's degree (MedTech - Functional Imaging, Conventional & Ion Radiotherapy, MSc, 2018-2020, Fachhochschule Wiener Neustadt) programmes.

Pécs, 20 August 2023

Date

Signature

Abstract

After the moiré fringes of two overlapping grids were studied by Lord Rayleigh it was concluded that the phenomenon could be useful as a test. Further research proposed moiré topography (MT) for the measurement of the human body. The main benefits of MT are that it is fast, non-invasive, non-ionizing and cost-effective. An algorithm, based on MT that is proved suitable for calculating the curvature angle of the spine, may also complement or substitute ionizing X-ray images. Since the processing of moiré images (MIs), however, requires several unique solutions, implementing a fully automated image analysis is challenging. The basic purpose of the research is to provide feasible and realistic answers for challenges indicated in Theses (1-5): (1) the reduction of the need for engineering in medical work and research applying MT, (2) providing a software-based framework for producing, segmenting and analysing MIs of scoliotic spine in diagnostic exploratory research, (3) identifying postural optima and (4) uniform surface topographic parameters in moiré imaging based on exploratory mathematical-geometric operations performed on MIs, (5) adaptive or empirical segmentation of MIs produced by XOR logic based on filtering and morphological operations. To address these challenges (1-5), the concept of Moiré Imaging Tool for Scoliosis (MITS) was designed as a user-friendly, software-based and exploratory research framework adapted to moiré research to generate, process and evaluate MIs of scoliotic spines. The viability of the segmenting function of the concept was illustrated with a prototype developed in MATLAB® environment. For the segmentation of MIs generated by XOR logic, two algorithms of empirically established filtering and morphological operations with static and adaptive function parameters are also proposed. The steps of the static algorithm include (1) enhancing contrast, (2) increasing brightness, (3) refining contrast, applying (4) 2-D Gaussian filter and (5) dilation, (6) thresholding and (7) skeletonization. The sequence of the adaptive algorithm follows (1) enhancing contrast based on root mean square (RMS) values, (2) applying 2D-Gaussian filter based on RMS values, (3) applying histogram equalization, (4) applying 2D-Gaussian filter based on peak signal-to-noise ratio, (5) calculating global image threshold using Otsu's method and (6) applying skeletonization. The segmenting methods are simple and, for the most part of the image, follow the moiré stripes accurately. Further research and development can make both algorithmic solutions suitable to replace time demanding and complex segmenting methods.

Keywords: moiré topography, computer-assisted image processing, research framework, software, scoliosis

Content

List of Abbreviations

2D or **2-D**	two-dimensional (or bidimensional)
3D	three-dimensional
BC	before Christ
BCD	back contour device
CAT	Contour Analysis Tool
def.	default
DPI	dots per inch
DVD	Digital Versatile Disc
FPS	frames per second
FST	Fringe Segmentation Tool
GUI	graphic user interface
ICT	Information and Communications Technology
IR	infrared
ISIS	Integrated Shape Imaging System
KPI	key performance indicator
L	left
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
px	pixel
R	right
R&D	research and development
RGB	Red, Green, Blue (color model)
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)

1 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 [1, 2, 3, 4, 5]. These postural or spinal disorders initially develop asymptomatically with consequences that can be felt over the following years of life, and are able to significantly change the quality of life by causing pain, serious deformations in the osteoarticular system and disorders of the internal organs [1, 6, 7]. Consequently, screening is considered as the most important factor preventing deformity from progressing [1]. For diagnosing body posture, objective methods are required. Today the gold standard for identifying changes in the spine position is the radiographic examination [8, 9, 10]. Having an increased sensitivity, children and adolescents are the most susceptible to radiation effects that can cause modification of genetic material [1, 11, 12, 13]. Disadvantages of X-ray imaging such as ionizing radiation, costs, time and repetition demands, the required tools and environmental conditions justify methodological research that can lead to fast, cost-effective and non-ionizing diagnostic imaging of the spine. As a method of school screening for scoliosis, several non-radiographic and non-invasive methods have been proposed [1] that include moiré topography (MT), raster stereography (Diers Formetric) [14, 15], 3D ultrasound imaging (the Scolioscan system) [16, 17], and Infrared Thermography (IR thermography) [18].

In 1970, as one of the first techniques applied in clinical diagnosis in topographic analysis, MT was proposed for examining the shape of objects in three dimensions [19]. 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. In addition, the technique does not require specially trained personnel. MT is used for the detection of early stages of scoliosis and different deformities of the spine [1]. 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 [1, 20]. The workload required for evaluation of MIs is, however, not inconsiderable; some researchers see the best solution for that in an automatic system [21, 22, 23, 24, 25, 26]. Processing of MIs requires several unique solutions that are influenced by the optical arrangement, nature of noise and detection, and applied illumination that has an especially significant effect on intensity distribution. Therefore, implementing a fully automated image analysis and evaluating solution is a challenging, nevertheless desired objective in the field [27, 28, 29]. These conditions induced this PhD research that aims (I) to summarize the theory of the moiré method (MM), and (II) to develop a 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.

1.1 Outline of Dissertation

Section 1 includes the introduction, the theses, and aims and methods of the PhD dissertation. **Sections 2-3** are theoretical sections. **In section 2**, the phenomenon of moiré is introduced, and a historical overview of moiré research from the 18th century to the present is provided. The introduction of the two main moiré techniques—the shadow and projection moiré—and a summary of advantages and disadvantages of MT are also dedicated parts of **section 2**. **In section 3,** MT and its medical technical applications are reviewed, first in general and then in the diagnostics of scoliosis. As part of the latter, a possible process of digital projection moiré imaging is also presented. **Sections 4-5** are practical sections. **In section 4**, based on gaps in exploratory analysis identified in moiré research, a software-based research framework concept for producing, processing and analysing MIs of scoliotic spines is proposed. For reducing uncertainties in moiré pattern analysis, **section** 5 proposes two algorithms for segmenting digital (projection) MIs generated by XOR logic. Summary and final conclusions are drawn in **section 6**. At the end of **sections 2-5**, a brief summary and directions for further considerations are given.

1.2 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 and research hindering factors.

1.2.1 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 [30].

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 [31]. 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 [31]. 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 [32]. 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.

Engineering work in moiré research can be divided into three main activity areas: (1) ensuring basic measurement technical conditions such as design, operation, maintenance and calibration of moiré equipment; (2) carrying out the measurements in cooperation with the medical staff, including the production of moiré images and optimization of methods and processes; and (3) meeting challenges in image processing, and image evaluation—i.e. segmenting MFs and analyzing segmented contour lines (for these challenges, see sec. 3.2 and sec. 5.). 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 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.

1.2.2 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 [23]. Therefore, although MT provides significant pieces of information about the subject, it is a serious drawback that conclusions may easily be drawn with ambiguity [33, 34, 35]. The lack of standardisation in surface topographical methods of the spine also leads to the fact that such techniques—for example, as MT itself, Scoliometer® and BCD 'back-contour device'—cannot be used interchangeably in clinical recording [36]. The standardised posture and the determination of gold standard parameters in relation to surface topographic examinations of spinal deformities are problems that need to be addressed and resolved [23, 24, 37, 38, 39]. The unification of surface topography parameters remains also an additional challenge—mainly for producers of surface topography equipment [39]. For MT applied in scoliosis, in this PhD research, only a need for standardisation was identified in the study of scientific literature but not a serious effort to invest. From 2012, in their literature review on the main characteristics of the MT, PORTO et al. also point out that there are more studies related to the application of MT than those that put a focus on the accuracy of the method itself and the standardisation of the measurements obtained [23]. In order to use the MT as an accurate screening tool, LABECKA and PLANDOWSKA in their more recent (2021) systematic review also emphasizes the need of a methodological standardization [1]. In other words, 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 [39]. To the problem of standardization, see sec. 3.2.2.

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 [40].

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 search strategy was developed using a Boolean combination of the keywords summarized in Table 2-3.

The literature search yielded 402 articles. After removing duplicates and elements from before 1990, 353 studies remained. Based on the analysis of the titles and abstracts, 6 studies were eligible for assessment by full paper, and 7 further studies were added from citations. 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. 1). The findings with abstracts and the phases of the literature review are written on DVD, as Digital Appendix A and B of the PhD dissertation.

Table 2: Applied method in advanced search of IEEE Xplore and PubMed

BLOCK Nr.	APPLIED METHOD IN ADVANCED SEARCH OF IEEE XPLORE AND PUBMED	
1	**IEEE XPLORE: “Document Title” OR “Abstract”** **PubMed: [Title/Abstract]** "moiré", "moire", "moiré topography", "moiré method", "shadow moiré", "moiré technique", "photogrammetry", "photogrammetric method", "moiré phenomenon", "projection moiré", "surface topography" **IEEE XPLORE: “Full Text .AND. Metadata”** **PubMed: [All fields]** "fringe analysis", "fringe detection", "fringe segmentation", "contour analysis", "contour detection"	
	Intra-block operator: OR	**Inter-block operator:** AND
2	**IEEE XPLORE: “Full Text .AND. Metadata”** **PubMed: [All fields]** “scoliosis” **IEEE XPLORE: “Document Title” OR “Abstract”:** **PubMed: [Title/Abstract]** "scoliosis", "spine", "body posture", "spine curvature", "column", "trunk", "trunk asymmetry", "anterior-posterior", "anteroposterior", "frontal plane", "sagittal plane", "transversal plane", "transverse plane", "adolescent idiopathic scoliosis", "idiopathic scoliosis", "screening scoliosis", "scoliosis evaluation"	
	Intra-block operator: OR	**Inter-block operator:** AND
3	**IEEE XPLORE: “Full Text .AND. Metadata”** **PubMed: [All fields]** "software", "instrument", "computer vision", "computer software", "tool"	
	intra-block operator: OR	**Inter-block operator:** -

Table 3: Applied method in advanced search of ScienceDirect

APPLIED METHOD IN ADVANCED SEARCH OF SCIENCEDIRECT
Search in “Title, abstract or author-specified keywords”: (moiré OR "moiré topography" OR photogrammetry OR "shadow moiré" OR "projection moiré") AND (scoliosis OR spine OR "body posture" OR "spine curvature")
Search in “Terms” (searching in all parts of the document for instances excluding references): "fringe analysis" OR "fringe detection" OR "fringe segmentation" OR "contour analysis" OR "contour detection" OR software OR "computer software" OR "computer vision" OR tool

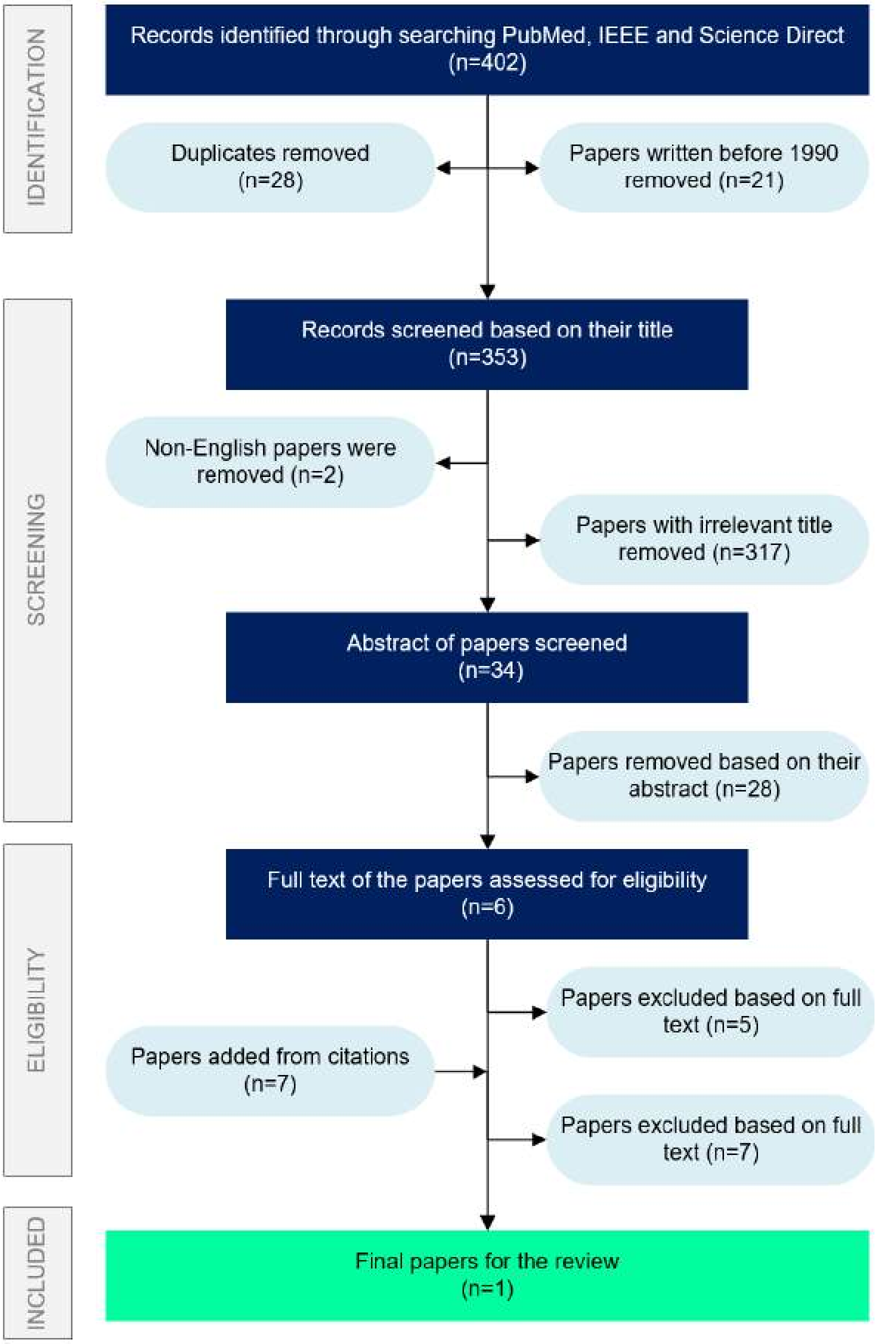


Fig. 1: The PRISMA flowchart of the literature review

Although structured light techniques and raster stereography systems—such as ISIS (Integrated Shape Imaging System) [35, 41], ISIS2 [42], Quantec [43, 44, 45], Jenoptik Formetric [46, 47, 48], DIERS Formetric 4D [49]—had been developed for assessing the degree of deformity in scoliosis based on the surface of the back, none of them[1] is adapted to the processes of producing, segmenting and evaluating MIs of scoliotic spines. The eligibility criteria of the review were fulfilled by a single study from 1996, where a computer vision system was proposed with segmenting and evaluating functions written in C programming language [51]. This software, however, is not available today, and there have also been significant advances in computer technology since this rather old system was developed.

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:

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

---

[1] The physical principle of MT is also used in DIERS' formetric measurement technology in combination with video-raster-stereography—as it is written in its product-portfolio brochure [50].

scoliosis via moiré imaging, and, thus, recommending globally applicable gold standard parameters.

1.2.3 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 [21, 22, 23, 24, 25, 26]. And yet, processing of MIs requires several unique solutions that are especially influenced by optical arrangement, applied illumination, and nature of noise and detection [27, 28, 29]. For reducing uncertainties in moiré pattern analysis, an accurate segmentation of MFs is vital. For the development of mathematical-geometric algorithms for evaluating MFs, an accurate segmentation is a basic condition.

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.[2]

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.

1.3 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).

---

[2] 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.

(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—sec. 2-3.

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—sec. 3.2.1

Method: Reviewing, generalizing and completing the process of a digital (projection) moiré technique presented by BALLA et al. [33].

(c) To address challenges introduced in theses (1-5) by designing (a) features with key functions and (b) 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—sec. 4-5.

Method: (1) Features and key functions are defined based on image processing and image evaluating problems of MIs of scoliotic patients. Selection of base 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 [52].

(d) To develop segmenting algorithms based on morphological operations for delineating MFs of scoliotic spines in MATLAB® environment—sec. 5.

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, made available by SALUS Ortopédtechnika Kft.[3]

(e) To conduct a SWOT analysis on MITS and MM used in scoliosis for exploring their viability for medical research—sec. 4.1.5.

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)

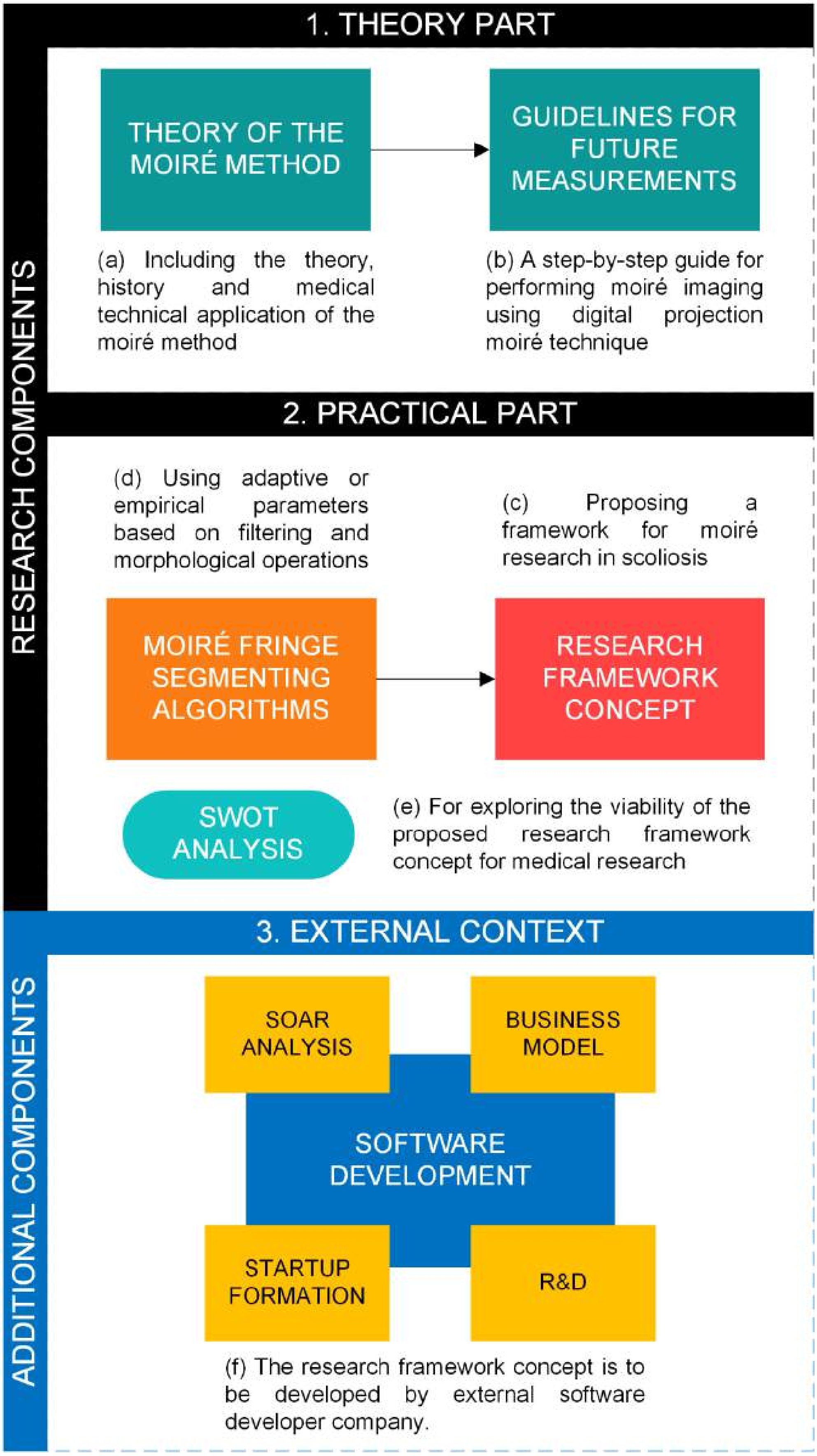
---

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

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

This research is a continuation and closure of a moiré study started in 2018. Therefore, the implementation of aims (a-d) is based mainly on the author's previous theses submitted (1) at the University of Pannonia for receiving an academic degree in Mechatronic Engineering (BSc, 2018), and (2) at the Fachhochschule Wiener Neustadt for receiving an academic degree in MedTech (MSc in Medical Engineering, 2020) [53, 54].

Fig. 2 shows the content of the dissertation in the context of aims (a-f).



(a) Including the theory, history and medical technical application of the moiré method

(b) A step-by-step guide for performing moiré imaging using digital projection moiré technique

(d) Using adaptive or empirical parameters based on filtering and morphological operations

(c) Proposing a framework for moiré research in scoliosis

(e) For exploring the viability of the proposed research framework concept for medical research

(f) The research framework concept is to be developed by external software developer company.

Fig. 2: The content of the dissertation in the context of aims (a-f).

2 Moiré: Phenomenon, Research and Techniques

The moiré phenomenon or moiré effect has long been known by the mankind. In ancient China, it was used to visualise a dynamic pattern as a decorative effect on watered silk [55]. The word moiré [mwaʁ e] can be traced back to the Arabic mukhayyar ‘cloth made from the wool of the Angora goat’ < lit. ‘select, chose’ which the English mohair derives from [55, 56]. Mohair was pronounced moiré by French silk weavers in the 17th century but instead of the name of the fabric it was understood as the wavy stripes (i.e. the moiré phenomenon) produced by glossy fabric fibres [55, 56, 57, 58, 59]. Therefore, moiré refers to an irregular wavy surface the pattern of which changes in accordance with its movement [55, 60]. Note that the word moiré does not refer to a person’s name as it is sometimes mistakenly assumed [60]. This is also indicated by writing the word moiré in lowercase letters—primarily in scientific literature written in English.

We can see the phenomenon of moiré, 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 can be observed (Fig. 3). In general, the dark fringes are called moiré stripes [23, 61]. We can also observe moiré stripes if two (or more) structures with different geometry overlap (Fig. 3d). The resultant fringes of original overlapping structures are not physical patterns, but rather optical illusions in the observer’s point of view. Classic everyday examples of moiré are the wavy folds of lace curtains and pictures about people wearing striped patterned clothes. In the first case, the small net structures are the ones that overlap, while in the second case, stripes and camera sensors or screen pixels interfere with each other. To generate mechanical interference of light by a superimposed network of lines, it is required that the angular deviation between the overlapping base lines is less than 45 degrees. The interference is formed by the intersection of base lines and determines the quality of the resulted moiré effect [23].

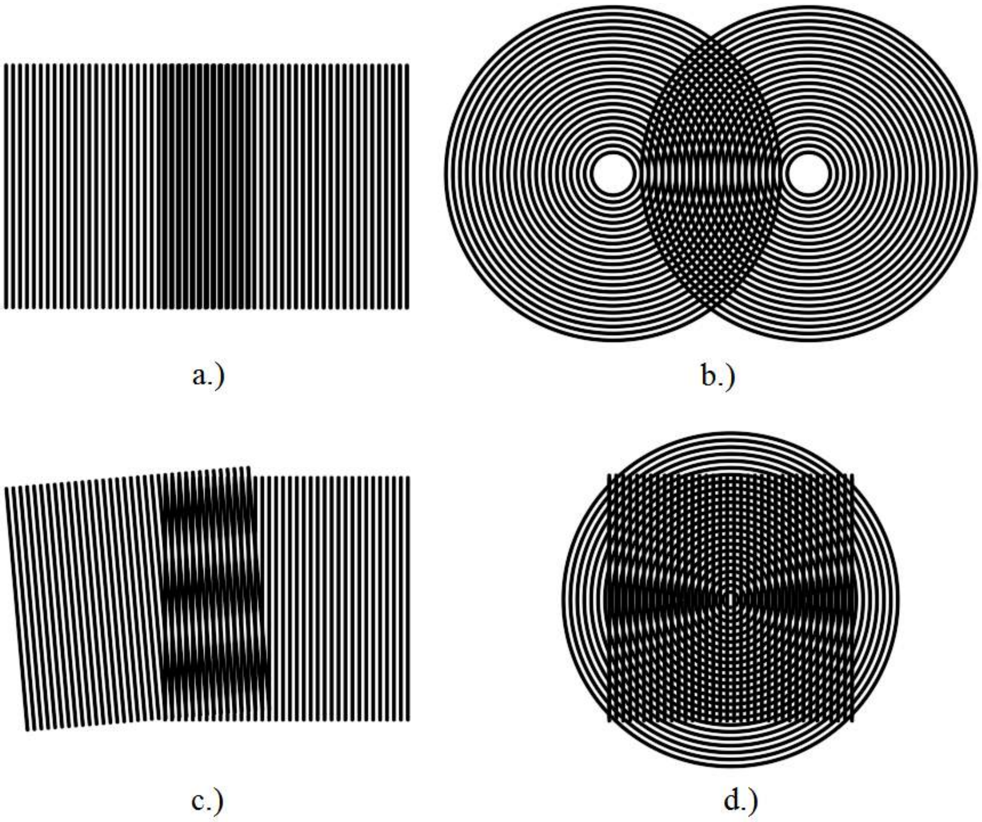


Fig. 3: Moiré patterns of geometric shapes
(a, b) identical, (c) identical but angle different, (d) different [11, 24]

2.1 Moiré Research: A Historical Review

In the historical review, an overview of the fundamental works leading to the current state of moiré research are presented. The two main sources of the review are the basic work of Theocaris [62] and the more recent work of Patorski [63] that also provides a detailed historical account.

In 1859, one of the three methods proposed by Foucault for testing lenses and optical systems by using low-frequency type gratings was MT. However, as he considered this method to be less sensitive than the knife-edge method,[4] he did not develop it further [62, 65]. This erroneous conclusion stemmed from the fact that he studied the moiré phenomenon exclusively in the light of geometric optics, and used only very low-frequency gratings [62].

---

[4] The knife-edge test was proposed as a simple method to evaluate the shape of concave optical surfaces. In the test, a point light source is located slightly off axis, near the center of curvature. If the optical surface is perfectly spherical, near the center of curvature, the reflected light forms a point image. A knife edge cutting the converging reflected beam of light casts a shadow on the surface. The surface is then evaluated according to the characteristics of the shadow that appears [64].

MFs were elevated to scientific status, first, by Lord Rayleigh dealing with diffraction gratings[5] in *The Philosophical Magazine* in 1874 [62, 67, 68]. He describes, that if two gratings containing the same number of lines to the inch be placed in overlap in such a manner that the lines are nearly parallel in the two gratings (minimal angular deviation), then (in the resultant pattern of the two gratings) a system of parallel bars develops itself, whose direction bisects the external angle between the directions of the original lines [67]. The distance between these parallel bars increases as the angle of inclination diminishes (Fig. 4). Due to the imperfection of the rulings, if the parallelism is closely approached, the bars become irregular. Lord Rayleigh concluded this phenomenon might be made useful as a test [62, 65, 67].

In 1887, Righi extensively dealt with the light distribution of resulting patterns of superposed bars. He also extended his study to variable cases of bar width as well as grating transmittance. He also studied the MF formation by combinations of overlapping circular and radial gratings with different centre-to-centre distances of the grating. Moreover, Righi produced MF patterns by parallel line gratings and applied them to the measurement of the relative displacement of the gratings [62, 65, 69].

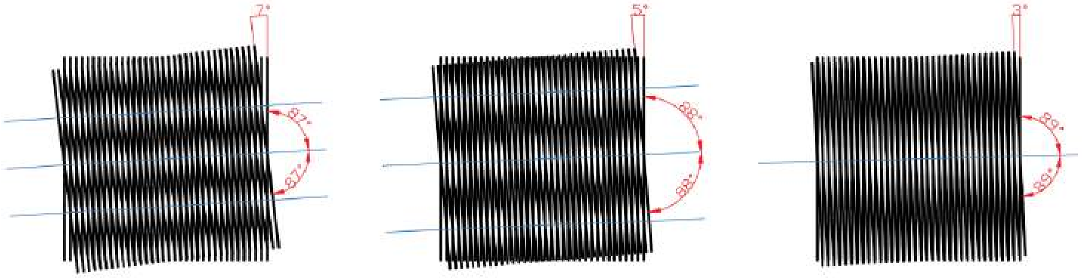


Fig. 4: Moiré fringes of identical grids with different angle deviations

As the angles enclosed by the overlapping grids decrease, the number of moiré patterns' parallel bright and dark fringes reduces. The directions of the fringe systems are indicated by guiding lines marked in blue the distance of which increases as the angles decrease [53, 70].

In 1922, the idea of Foucault's method was used by Ronchi for the optical testing of lenses and mirrors (Ronchi test).[6] To generate MFs, Ronchi illuminated the optical system under test by a point source, and placed a low-frequency grating at the vicinity of the image of the light source. This pattern, as it is affected by any aberration of the optical system, is suitable for localizing defects. Thus, this equipment is considered essentially as a sensitive achromatic

---

[5] 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 [66].

[6] The Ronchi test is seen by some as an extension of Ritchey's wire test which extends the knife edge method of Foucault to aspherical surfaces [71].

interferometer [62]. Later (1925) RONCHI also studied the moiré pattern formed by the overlap of a line and a circular grating. It was shown that the MFs of the superimposed gratings depended on the grating pitch, and they show hyperbolic, parabolic and elliptic patterns [62]. The geometrical pattern used for quantitative measurement can be regular or random. This technique, when a regular pattern in the form of a grid is used, is called the moiré method; other names are deflection mapping or the RONCHI method (with a Ronchi grid) [72].

RAMAN and DATTA applied[7] parametric equations at describing moiré patterns—comprised parallel line fringes (Brewster bands) or families of circles—generated by the overlap of two zone gratings with different centre-to-centre distances [62, 75]. The description is parametric because, when writing equations, they switched from a MF to the adjacent one by applying parameters [27, 63].

Until the middle of the 19th century, the metrological benefits of the observations of FOUCAULT, RAYLEIGH, RIGHI, RONCHI, RAMAN, and DATTA 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 1945, TOLLENAAR gave an interpretation of the moiré phenomenon based on geometric optics [76]. He described the characteristic properties of MFs produced by coarse gratings of equal or just slightly different pitch in terms of their relative rigid-body translation, angular displacement or deformation [62, 76]. By applying the properties of MFs, KACZER and KROUPA determined (1952) the strain components in a 2D strain field [62]. Meanwhile, the problem of producing quality gratings for metrological application at a moderate cost was resolved by a novel principle introduced by SIR THOMAS MERTON [77]. This gave a significant boost for efficient measurements and created new fields of application of MFs in measurement processes [27].

For almost a full century following the observations of LORD RAYLEIGH and RIGHI, the theoretical analysis of moiré phenomena has been based on purely geometric or algebraic methodologies. Based on these approaches, many special purpose mathematical developments have been elaborated for the needs of specific applications such as strain analysis and metrology [60]. The classical geometric approach considers geometric properties of the superposed layers, their periods and their angles. By considering relations between geometric entities such as triangles, parallelograms generated between the superposed layers, this method—under certain limitation—allows the development of formulas that can

---

[7] In 1925, DATTA published with RAMAN [73]. The next phase of their work was published exclusively by DATTA in 1927 [74].

predict the geometric properties of the moiré patterns [60]. Notable representatives of the classical geometric approach are NISHIJIMA [78], TOLLENAAR [79] and YULE [80].

Another widely used classical approach is the pure algebraic indicial equations method that is based on the equations of each family of lines in the superposition, which also yields the same basic formulas [60, 81]. A more recent approach uses the theory of non-standard analysis for examining the moiré phenomenon [82]. This approach, in addition to the basic geometric properties, can also provide the intensity levels of moiré patterns. However, the best adapted approach for investigating phenomena in the superposition of periodic structures is considered to be the spectral approach that is based on the Fourier theory [60].

The Fourier theory in the study of moiré phenomena was first applied in the 1960s and 1970s. This approach, unlike the previous methods, enables analyses of moiré properties not exclusively in the original layers and in their superposition, but also in their spectral representations, and thus—as AMIDROR says—“offers a more profound insight into the problem and provides indispensable tools for exploring it” [60]. The Fourier theory can be divided into two distinct stages [60]: The first is the use of Fourier series decompositions purely in the image domain for representing the original repetitive structures, their superposition and their moiré patterns [83]. In the second stage, further elements of Fourier theory were introduced such as the dual role of the image and the spectral domains [84, 85], and, also, the interpretation of MFs in spectral terms as an aliasing phenomenon [86]. Since then, however, the Fourier approach has been used only adapted to some particular applications [87, 88, 89], and no systematic effort has been made to explore full possibilities it offers [60]. As a possible reason for this, AMIDROR stresses some branches of mathematics that are not very widespread (i.e. the theory of almost-periodic functions and geometry of numbers), and that are inevitable to face in any systematic attempt [60]. The reason for the stagnation of moiré-related publications in the second half of the 1970s is attributed to problems—mainly in image evaluation—that due to a lack of adequate computing capacity, could not yet be addressed [27]. With the development and spread of computer technology, the amount of scientific research and publications related to moiré has started to increase again. Among others, research on metrology and optics have a significant impact on the moiré technique—but this is also true backwards as the moiré technique solved several measurement technical tasks that had not been possible before [27]. Research on moiré patterns is also considered extremely useful to help understand basic interferometry and interferometric test results [55]. Problems in the analysis of moiré phenomena have also had a positive effect on the development of other disciplines such as signal processing, digital image processing, artificial intelligence, etc [27]. The present work, also, aims to contribute to solving problems in digital processing and evaluation of MIs.

In the 1970s, beyond industrial applications, further research proposed the MT for measurement of the human body, and subsequent medical technical research proved how many potential fields of applications the MT has—especially in Japan where pioneering works were performed [19, 24, 30, 90, 91]. From the 1980s till present, depending on the moiré technique applied, 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 medical technical applications of the MM will be discussed in detail in sec. 3.

2.2 The Shadow and Projection Moiré Techniques

Based on the physical phenomenon of moiré, moiré techniques are defined as a group of methods usually used for surface mapping and shape or deformation measurement [23, 92]. 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) [93]. From the resultant moiré pattern of these two structures we can conclude the deviation between the two states of the object examined. In other words, if we know one state of the surface, we can conclude from the resultant moiré phenomenon another state [27]. The formation of the moiré phenomenon can be interpreted as a sampling process, where the association of the projection grid and another (reference) grid with the same spatial frequency means essentially equidistant sampling [93].

Moiré techniques are stereometric methods of 3D analysis of an object from a 2D image [22, 23, 37, 94]. They differ in regards to the different ways the moiré patterns are created and processed in the topographical analysis [23]. MT is a simple method that requires only a camera (detector), a light source and a grid, and is used to measure and display the surface of 3D bodies. The formation of depth contours by arranging the light source and viewing point at the same distance from the (projection) grid is a key feature of MT [95]. This concept was formulated independently by MEADOWS et al. and TAKASAKI in 1970 [27, 63, 95]. MIs comprise alternating bright and dark fringes [21, 22, 37, 51]. Usually, as already mentioned above, dark fringes are called moiré stripes but we can also consider bright ones as moiré surfaces when examining MIs—it is only a matter of agreement [27].

Moiré effect can be produced by several techniques; even by such base grids that are not necessarily physical objects as in case of the shadow moiré and projection moiré techniques

(SMT and PMT, respectively). SMT uses a single physical grid and its own shadow projected onto the examined surface to generate interference and moiré pattern. In PMT a base grid is projected onto the surface, but the moiré pattern is generated afterwards by applying virtual grids via software post-processing [20, 23, 96]. In the scientific literature, SMT and PMT seem to be the two primary methods of MT used for measurement of the human body [23, 97].

2.2.1 Shadow Moiré Technique

The SMT was presented by Takasaki [19, 90] in the early 1970s. Takasaki's work is known as the first example of a successful study of the moiré phenomenon applied for 3D measurements [23, 28]. In the SMT, the moiré phenomenon is created by the overlapping of a single reference grating and its shadow projected on the surface (Fig. 5).

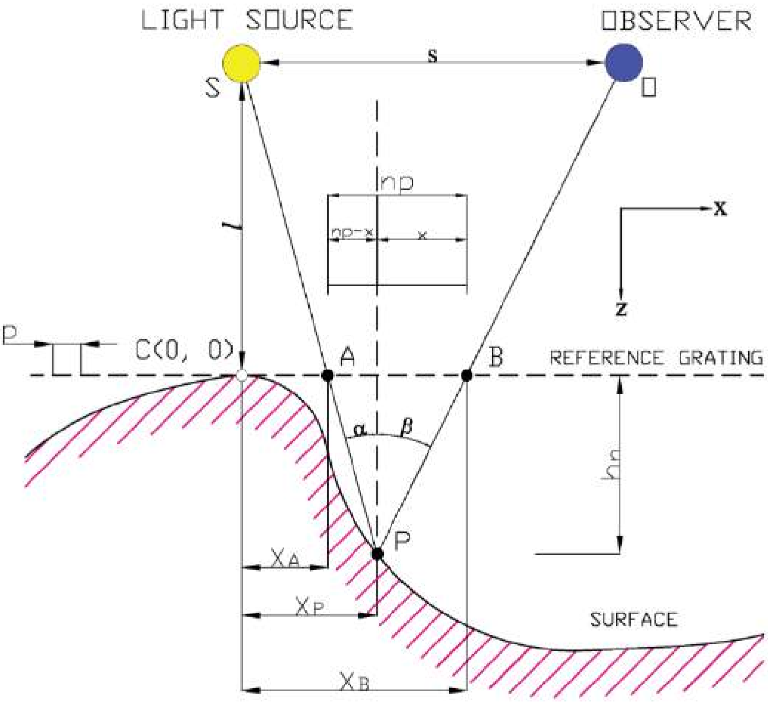


Fig. 5: Optical arrangement of the shadow moiré technique [53, 70].

(A)	Point where source light (S) passes through the reference grating
(B)	Point where source light (S) reflected passes through the reference grating
(C)	Origin
(O)	Observer
(p)	Grating pitch (or period of the grating)
(P)	Measured point
(S)	Light source
(α)	Incidence angle (of incoming light)
(β)	Viewing angle
(h_n)	Depth of n^{th}-order moiré pattern measured from the reference grating
(l)	Distance of S and O from the reference grating surface
(n)	Order of the moiré pattern
(s)	Interseparation of S and O

(X_A)	X component of SA
(X_B)	X component of SB
(X_P)	X component of SP
(x)	X component of P and B

The reference grating positioned in front of the examined surface area is illuminated with a perpendicular point light source (S). Therefore, a shadow grating is produced that becomes distorted in correspondence with the surface characteristics [98]. For the observer (O) that is s distance from, and parallel to, the light source, the moiré phenomenon which results from the grid and its own shadow on the surface, becomes visible. Fig. 6 shows an example of SMT applied on the human back. As it follows from its concept, SMT requires a master grating that is as large as the object being studied [99].

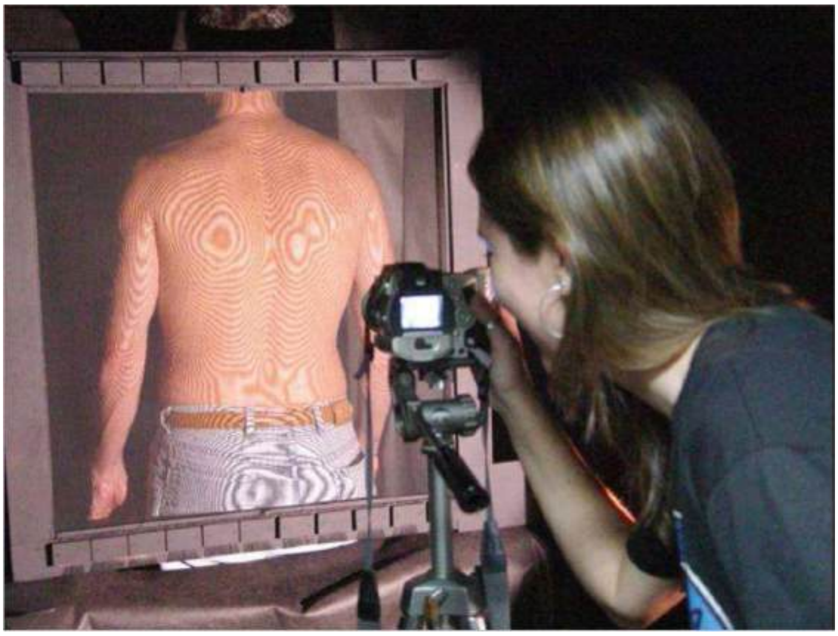


Fig. 6: Shadow Moiré Technique applied on the human back [23]

2.2.1.1 Relations of surface identification in shadow moiré

The third (z-axis) coordinate of a surface point (h_n) can be calculated on a MI by following Equations 1–21. Fig. 5 and derived mathematical relations are based on the contracted interpretation of ANTAL’s [93] and Yoshizawa’s [100] illustrations and inferences.

Supposing that distance OA and OB contain i and j number of grating elements

$$OA = ip, \tag{1}$$

and

$$OB = jp, \tag{2}$$

the AB distance is

$$AB = OB - OA = jp - ip = np, \tag{3}$$

where

- $n = 0, 1, 2, 3, \ldots$ is the MF order that is equal to the position in the order of successive moiré surfaces [27].
- p is the grating pitch of the reference grid.

Based on the similarity of the triangles SOP and ABP, we can write

$$\frac{h_n + l}{s} = \frac{h_n}{np}, \tag{4}$$

where

$$np = h_n + \tan\alpha + h_n + \tan\beta = h_n(\tan\alpha + \tan\beta). \tag{5}$$

Substituting Equation (5) into (4) we get

$$\frac{h_n + l}{s} = \frac{h_n}{h_n \tan\alpha + h_n \tan\beta}, \tag{6}$$

and dividing by h_n on the right-hand side we obtain

$$\frac{h_n + l}{s} = \frac{1}{\tan\alpha + \tan\beta}, \tag{7}$$

where we express $\tan\alpha + \tan\beta$ by taking the reciprocal of both sides

$$\tan\alpha + \tan\beta = \frac{s}{h_n + l}. \tag{8}$$

Considering the triangle ABP, we can segment the distance $AB = np$ as

$$h_n \tan\alpha = np - x \qquad and \tag{9}$$

$$h_n \tan\beta = x\,, \tag{10}$$

from which the tangents of the two angles are

$$\tan\alpha = \frac{np - x}{h_n} \qquad and \tag{11}$$

$$\tan\beta = \frac{x}{h_n}. \tag{12}$$

Adding up Equations (11) and (12) gives

$$\frac{np - x}{h_n} + \frac{x}{h_n} = \tan\alpha + \tan\beta. \tag{13}$$

Simplifying the left-hand side we get

$$\frac{np}{h_n} = \tan\alpha + \tan\beta, \tag{14}$$

from which expressing h_n gives

$$h_n = \frac{np}{\tan\alpha + \tan\beta}. \tag{15}$$

Since, according to Equation (7),

$$\frac{h_n + l}{s} = \frac{1}{\tan\alpha + \tan\beta}\ ,$$

therefore,

$$h_n = \frac{np(h_n + l)}{s}\ . \tag{16}$$

Splitting Equation (16) into two halves on the right side

$$h_n = \frac{nph_n}{s} + \frac{npl}{s}, \tag{17}$$

and multiplying both sides by s

$$sh_n = nph_n + npl\,, \tag{18}$$

then subtracting nph_n

$$sh_n - nph_n = npl\,, \tag{19}$$

and multiplying out h_n we get

$$h_n(s - np) = npl\,. \tag{20}$$

Finally, dividing by $s - np$ we express h_n—the depth coordinate of the moiré surface

$$h_n = \frac{npl}{s - np}\,. \tag{21}$$

We can see by Equation (21) that the moiré stripes are contour lines at given depths measured from the reference grid. The width of the reference grid must not be less than 1.0 mm, otherwise diffraction effect appears in the image [98]. The sensitivity of SMT depends on the angle of illumination and that of the observer's view. In general, the larger the angle between the illumination and the observer's view, the more sensitive the measurement [101]. Since in practice the distance between illumination and observer is not infinite, the mathematical relations for surface identification outlined above may become more complex depending on the design of the moiré equipment. The interpretation becomes difficult by the condition that the contour interval is dependent partially on the actual height of the surface. This difficulty can be avoided by positioning the reference grid as close as possible to the surface to be examined, so that the height h_n is small compared with the illumination and viewing distances [101]. Besides these contours, the study of intensity distribution of MFs can also lead to interesting results. We can approximately identify the points of the surface by knowing the order number (or fringe order) n of a contour line (e.g. Fig. 7). If we know further details about the intensity distribution of that MF, we can exactly plot the measurement point [100].

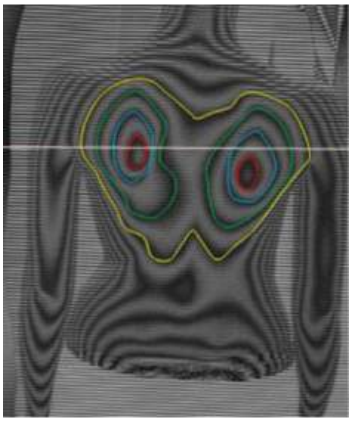


Fig. 7: An illustration of moiré fringe orders on the human back.
Yellow–0th order, green–1st order, blue–2nd order, red–3rd order [102].

2.2.2 *Projection Moiré Technique*

For producing the moiré phenomenon, the PMT [103, 104] uses two gratings with the same properties: one for projection and another for reference required for detecting moiré patterns (Fig. 8).

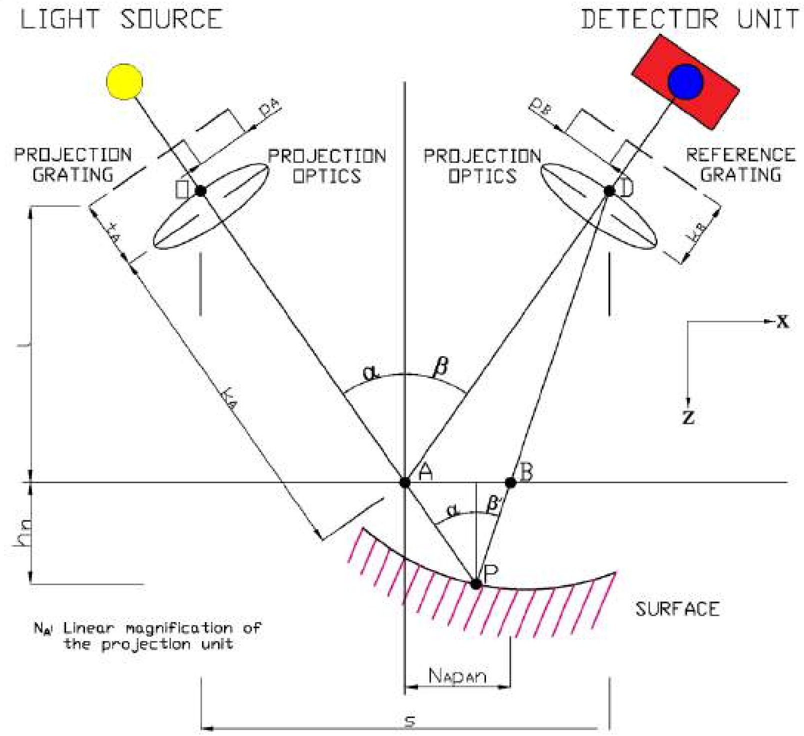


Fig. 8: Optical arrangement of projection moiré technique [53, 70].

(A)	Point where source light passes through the reference plane
(B)	Point where source light reflected through the reference plane
(D)	Projection optics on the detector's side
(h_n)	Depth of nth-order moiré pattern measured from the reference plane

(k_A)	Distance between (A) and projection optics on the illumination's side
(k_B)	Distance between the reference grating and optics on the detector's side
(l)	Distance of projection and reference grating measured from the reference plane
(n)	Order of the moiré pattern
(N_A)	Linear magnification of the projection unit
(O)	Projection optics
(P)	Measured point
(p_A)	pitch of projection grating
(p_B)	pitch of reference grating
(s)	Distance between the projection optics (O) and (D)
(t_A)	Distance between the projection grating and optics on the illumination's side
(α)	Incidence angle (of incoming light)
(β)	Viewing angle at (A)
(β')	Viewing angle at (P)

By the optical system, the projection grid is projected to the examined surface, creating a linear base grid. Then the detector takes a picture through the reference grating of the object's surface and the base grid on it. To the observer, the moiré phenomenon becomes visible as the resultant pattern of the reference grid and the distorted base grid on the object's surface [93, 100]. These grids can be physical materials (e.g. plates made of liquid crystal) or software-generated. For in the latter case, a software-generated base grid is projected onto the surface using a projector. Then, a photograph is taken of the distorted grid having information on the surface characteristics. To that photograph, the reference grid is applied by software as an additional layer as a result of which the moiré phenomenon is produced [100]. Fig. 9 shows the concept of PM for human back examinations.

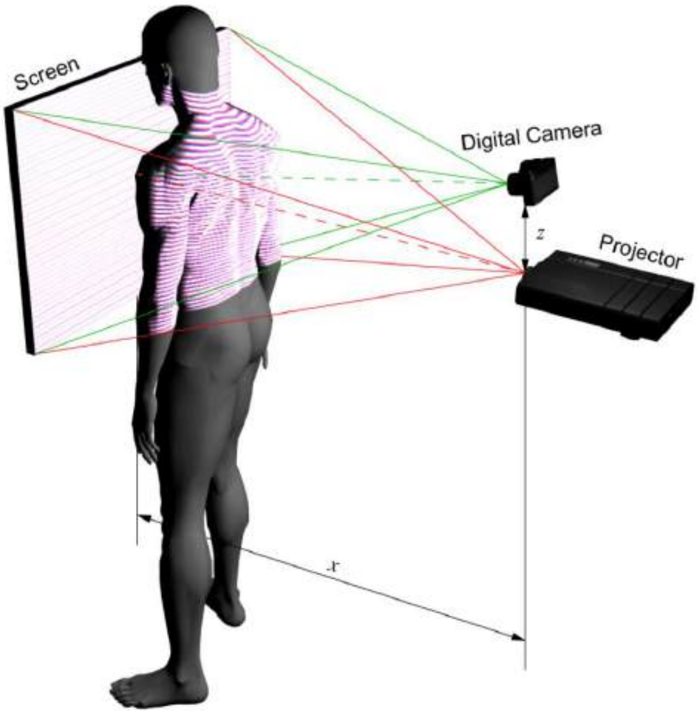


Fig. 9: Classical moiré projection layout for human back examinations [105].

The parameters of software-generated MIs, such as measuring range and resolution, can flexibly be changed according to given surface properties. It is also possible to generate moiré phenomenon by modelling the object to be measured, and to use it as a reference in comparison with results obtained when measuring real surfaces [65]. Here, we note that phase-shift and frequency sweeping methods can facilitate fine-tuning and analysis of moiré patterns produced by SMT [106, 107, 108] and PMT [109, 110]. For this, in case of projection technique, one of the two grids is rotated or moved to the desired distance from the surface. Then, resulting moiré patterns can be evaluated using appropriate algorithms [100].

2.2.2.1 Relations of surface identification in projection moiré

The determination of depth coordinates of a PMT-generated MI is presented below based on ANTAL's guidance [93]. For the calculation, similar to SMT, geometric relations of triangles are used. Highlighting the shapes enclosed by the points O, D, P and A, B, P in Fig. 8, the following triangles are obtained, shown in Fig. 10.

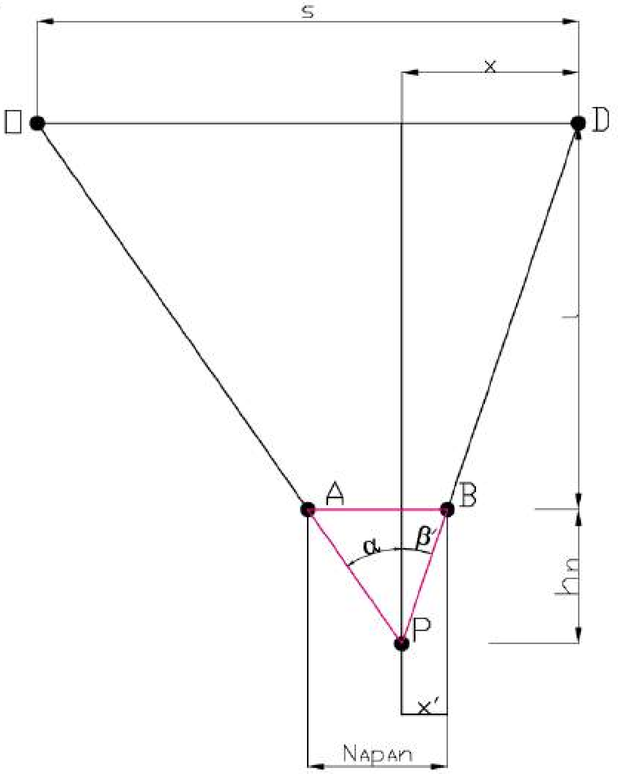


Fig. 10: Geometric points of the projection moiré model: the triangles ODP and ABP [53].

Based on trigonometric functions related to the triangle ABP, the tangent of the two angles is

$$\tan\alpha = \frac{N_A p_A n - x'}{h_n}\ and \tag{22}$$

$$\tan\beta' = \frac{x'}{h_n}. \tag{23}$$

Adding up Equations (22) and (23) gives

$$\tan\alpha + \tan\beta' = \frac{N_A p_A n - x'}{h_n} + \frac{x'}{h_n}. \tag{24}$$

Simplifying the right side we get

$$\tan\alpha + \tan\beta' = \frac{N_A p_A n}{h_n}. \tag{25}$$

Expressing h_n from (25) the depth is

$$h_n = \frac{N_A p_A n}{\tan\alpha + \tan\beta'}. \tag{26}$$

The procedure is similar for a triangle formed by the points O, D, P, where the tangents of the two angles are

$$\tan\alpha = \frac{s - x}{h_n + l}\ \text{and} \tag{27}$$

$$\tan\beta' = \frac{x}{h_n + l} \tag{28}$$

Adding up Equations (27) and (28) we get

$$\tan\alpha + \tan\beta' = \frac{s}{h_n + l} \tag{29}$$

Expressing $h_n + l$ the depth is

$$h_n + l = \frac{s}{\tan\alpha + \tan\beta'}. \tag{30}$$

The linear magnification of the projection unit is

$$N_A = -\frac{i_A}{o_A} \tag{31}$$

Based on the Gaussian lens formula (also known as the thin lens equation) the relationship between focal length f, image distance i and object distance o is

$$\frac{1}{f_A} = \frac{1}{i_A} - \frac{1}{o_A}. \tag{32}$$

The trigonometric function related to i_A is

$$i_A = \frac{l}{cos\alpha} \tag{33}$$

Expressing o_A based on Equations (32) and (33)

$$o_A = \frac{f_A l}{f_A cos\alpha - l} \tag{34}$$

Substituting Equation (33) and (34) into (31) then simplifying, the linear magnification N_A is

$$N_A = \frac{l - f_A cos\alpha}{f_A cos\alpha} \tag{35}$$

Let $h_n \ll l$ be and assume similar focal lengths and grating pitches.

$$l + h_n \approx l \tag{36}$$

$$f_A = f_B = f \tag{37}$$

$$p_A = p_B = p \tag{38}$$

So Equation (26) can be given as

$$h_n = \frac{N_A pn}{\tan\alpha + \tan\beta'} \tag{39}$$

Substituting Equation (29) into (39), we get

$$h_n = \frac{N_A pn(l + h_n)}{s}. \tag{40}$$

Considering Equation (36), the depth coordinate is

$$h_n = \frac{N_A p n l}{s}. \quad (41)$$

The mathematical relations show that the depth analysis of images produced by using PMT is similar to that of the shadow technique. One distinct advantage of PMT is that it requires only a small transparency of the reference grating. Furthermore, when a physical reference grid is used in PMT, it is not required to be as large as the object being studied (as for the shadow method). Using PMT, if the surface is not initially flat, its out-of-plane displacement can be measured from only one double-exposure photograph. With SMT, to calculate contour differences, two separate fringe photographs are required. With PMT, contour differences of two entirely distinct objects are easily determined [99].

2.3 General Statements on Advantages and Disadvantages of the Moiré Topography

General considerations on the advantages of MT are reviewed based on the nine-point summary of PATORSKI [63]. As disadvantages of MT are not specifically addressed by PATORSKI, they are presented considering ANTAL's [27]—partly experience and partly literature-based—summary. Based on PATORSKI, advantages of MT are also summarized by PAVELYEVA [111] and PAAKKARI [95].

The main advantages of MT are as listed below (1-9) [63]:

(1) Measurements are whole-field, an advantage over point-by-point or line methods. Total surface deformations and local occurrences can be studied, also under transient experimental conditions. These have an advantage over discrete point sampling methods.

(2) Due to the relatively fast data acquisition and processing, investigations can be done in quasi-real-time (QRT) and automated.

(3) Profiles are given in the form of 2D contours.

(4) Contouring of specularly reflecting and light scattering surfaces is possible.

(5) The effect of local surface abnormalities may be eliminated by averaging.

(6) The resolution may be varied.

(7) Both differential and absolute measurements are possible, thus, the effect of system geometry and optical aberrations can be eliminated

(8) Both static and dynamic events can be studied.

(9) The method is simple and fast to operate.

Disadvantages of MT are summarized (1-5) [27]:

(1) The variable resolution mentioned in the advantages is problematic for the application. This means that reducing the resolution is rarely necessary, but increasing it encounters technological limitations, or can only be achieved at the expense of other metrologically relevant features.

(2) Thorough surface analysis requires very serious considerations and post-processing.

(3) Despite the principle and layout simplicity of the measurement, it is not simple to achieve high contrast.

(4) The layout and the geometry of the measurement have a decisive effect on the moiré phenomenon. Therefore, their anomalies require thorough analysis in terms of measurement applicability and error correction.

(5) Examination of high-slope surfaces is problematic.

2.4 Conclusion and Further Thoughts

Although the phenomenon of moiré has been known since ancient times, its measurement technical potential only became clear in the 19th century. From this time, MFs were elevated to scientific status and became the subject of research by many researchers. Until the middle of the 20th century, though, the metrological benefits of scientific observations on moiré did not enjoy the attention that they deserved. After the problem of producing quality gratings for metrological application at a moderate cost was resolved, 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. From the 1970s, beyond industrial applications, MT has been used for measurement of the human body. Although MT provides a non-invasive and non-ionizing method for analysis of 3D profiles in the form of 2D contours with relatively fast data acquisition in quasi-real-time and at low-costs, comprehensive surface analyses require serious considerations and labour-intensive post-processing. This requirement for evaluating and segmenting MFs includes methods that are suitable for drawing unambiguous conclusions on the subject of the study—and this becomes especially important in medical examinations. Successful development of any healthcare technology is a complex process that requires contributions from different disciplines, such as medicine and engineering. In the development of software-based segmenting and evaluating methods, although not in equal proportions, a focused medical and engineering knowledge is substantial in cooperation. Insufficient work organization and communication between engineers and medical specialists may lead to faulty calibrations of moiré equipment and inadequate analysis of moiré patterns, and thereby, to underutilized potential of MT—as TAKASAKI reports in the early 1980s [30]. 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.

3 The Moiré Method and its Medical Technical Applications

Beyond industrial measurements, the MT also allows the topographical analysis of the human body. The application of MT in antropomorphology was first reported by TAKASAKI in 1970 [19, 90, 91]. MT allows non-invasive, non-ionizing and cost-effective measurements with an unlimited number of repetitions [33, 102, 112]. Using MT in the topographical analysis of the human body can indirectly identify areas with structural deformities under the skin through the form of the body surface [23, 113]. This makes the importance of R&D of MT in a clinical setting particularly justified.

3.1 Moiré Topography for the Measurement of the Human Body

It appears in the scientific literature that in the measurement of the human body some MTs are more commonly used [23]. In the topographical examination of the spine and trunk, the SMT appears to be the most effective. This can also be explained by the fact that this was the first moiré technique applied to the human body [19, 23]. However, in 1983, NAGASHIMA et al. used PMT to generate a surface model of the human trunk [114]. In their 1991 study, MOGA and CLOUD also used PMT to measure the motion of the scapular mechanism as a function of upper arm adduction [115]. Their study differs from other biomechanical applications of MT in that the visualization and evaluation of moiré contours—being a motion study—was not only bound to a single state of the body, but images of multiple positions were analyzed. From the 2000s, PMT has been increasingly used in research—especially in the study of postural defects. This is best explained by the development of image processing [23], which makes the application of MT even on surfaces of fine and more complex topography successful. Examples of such areas are bones and teeth, for which WOOD et al. used moiré interferometry[8] analysis [117, 118, 119].

Medical applications of MT include the early detection of scoliosis [36, 120, 121] and the examination of other spinal deformities (hyperkyphosis, hyperlordosis, planar back, gibbosity) in different planes (sagittal, frontal, transverse) from only a single image obtained [21, 23, 122, 123, 124]. Non-invasive reconstruction of the vertebral column based on the generated moiré topograms have also been studied using classical 2D sequential digital filter and cellular neural networks [125].

---

[8] In moiré interferometry, the concepts of geometrical moiré technique and optical interferometry is combined. Moiré interferometry allows the measurement of in-plane displacements with very high sensitivity [116].

In spinal examination, further applications of MT are aimed at mapping postural defects, where SMT [123, 126] and PMT are also used [127]. UETAKE et al. [126] used an SM device developed by TAKASAKI [19] to study and compare spinal curvature characteristics of Japanese sportsmen. They found that the posture was specific to the sport. PORTO et al. also used SMT in a population study of postural evaluation of individuals of over 60 years of age [128].

Remaining on the subject of the human back, there is no generally accepted convention in clinical practice to describe the position and movement of the scapula relative to the thorax [113]. To clearly determine the position of the scapula, it is sufficient to identify three points of its coordinates in 3D space. Since MT allows to indirectly identify places of structural deformities under the skin [23] and also skeletal structures, CHALUPOVÁ used SMT to describe the scapular region and symmetry relative to the spine [23, 113]. In their experimental biomechanical study, JELEN and KUSOVÁ aimed at semi-automatic and automatic evaluation of moiré contour lines to monitor the dynamics of a woman's axial skeletal system during and after pregnancy [129].

ASUNDI has demonstrated the use of a SM device to measure the foot pressure distribution [130]. The foot pressure distribution has a significant importance in orthopaedics: this provides information not only on the structure and function of the foot, but also the posture regulation. Thus, medical professionals—especially orthopaedist, physiotherapists and orthopaedic footwear designers—may be in possession of useful information acquired by MT. To measure the longitudinal vault of soles, MROZKOWIAK used a device based on PMT (Posturometer M) [131]. In addition to the spine and soles, YERAS et al. examined adolescents aged 12–15 years and further shape characteristics and disorders of legs [23, 121]. As for the face, LAY et al. proposed SMT in face profile measurements for 3D face recognition purposes [98]. KATSUKI et al. attempted to quantify the state of symmetry of the nose for cleft lip operation using the SMT [132, 133].

Another example of the widespread use of MT for topographic and biomechanical measurements is in the fields of dental research and forensic odontology. Research by TAKEI et al [134] examined the characteristics of palatal growth and development of Japanese children and adolescents aged 3–17 years by taking head, face, bone, palate and tooth measurements using 3D measuring methods for a spatial system of coordinates and SMT. Sex identification by oral cavity and dental arch was another object of this study, where the specimens consisted of 200 maxillary plaster casts of Japanese males and females aged 15-49 years. Based on the applied mathematical analysis of MIs of the plaster casts, the gender was correctly identified with a rate of 93% accuracy. Based on SMT, Sex identification was also performed on maxillary canines of 52 Japanese males and females taken from four directions (labial, palatal, mesial, distal). Correct identification of the sex was accounted with an accuracy of 84.6%. In their conclusion, TAKEI et al also introduce other possibilities for the applications of the MT such as age estimation, paternity tests, preparation of restored facial images and classification of facial forms from an anthropological standpoint.

KANAZAWA et al [73] applied moiré contourography for three-dimensional measurements of the occlusal surfaces of upper molars. It was observed that the MT is suitable for analyzing small amounts of wear that was difficult to quantify. MT was, however, not recommended when the wear pattern included greater convexity of the tooth crown or the central fossa [71, 73].

In biomechanical studies, moire interferometry was used to understand the mechanical and temperature change induced stresses and strains in tooth structure [74, 135, 136, 137]. By using moiré interferometry, WOOD et al evaluated the effects of changes in humidity on the dimensional changes in dentin disks constrained by enamel land in unconstrained dentin [118]. They concluded that moiré interferometry is a powerful tool to study the deformation of materials that are not isotropic and are not linearly elastic. Deformations observed in their study indicated that the zone of dentin-enamel junction is a unique material interface that needs to be better understood in terms of normal tooth function.

WANG and WEINER used MT with higher-density gratings to study strain-structure relationship in enamel and dentine [138]. Their study was consistent with the hypothesis that within the dentin there are structural adaptations for transferring and minimizing stress as they concluded that the strain exhibited in the enamel is significantly lower than that in the dentine [71, 138]. Based on moiré interferometry, WOUTERS et al. developed a sensitive measuring method for direct evaluation of gingival swelling [139]. They concluded that the method applied, although warrants further evaluation, has potential application in clinical experimental research.

3.2 Moiré Topography in the Diagnostics of Scoliosis

The different spinal deformities have been in the focus of medical attention for thousands of years. We can find references and medical advice to the treatment of scoliosis in ancient Hindu religious texts (3500-3000 BC) and Egyptian injury care guides (2600-2200 BC) [140]. The Hippocratic Corpus (lat. Corpus Hippocraticum) mentions the lateral curvature of the spine, and terms like scoliosis, kyphosis, lordosis created by GALEN (129-216?) show the all-time validity of our topic. Referring to the importance of the treatment in scoliosis, the French physician NICOLAS ANDRY (1658-1742) on a title page of his famous work *Orthopaedia: or the Art of Correcting and Preventing Deformities in Children* proposed a picture of a crooked tree tied to a stake as the symbol of the orthopaedic profession [141].

The traditional diagnostics of scoliosis is performed by orthopaedists in a painless examination called the forward bending test [94]. This method, however, beyond the fact that it may produce too subjective results, is not reproducible and time-consuming [94]. It is also common that physicians perform examinations manually based on radiographs, but these evaluations are still time-consuming and, in the case of larger groups (e.g. in school screenings) they may be inaccurate [142]. Depending on the medical practice of the region, for an accurate diagnosis, it is important to provide X-ray images with front and back views of the spine in standing and in forward bending position and with a lateral view [33, 142]. In the diagnostics of scoliosis, the so-called Cobb angle, measured on radiographs (Fig. 11), is considered the gold standard [34].

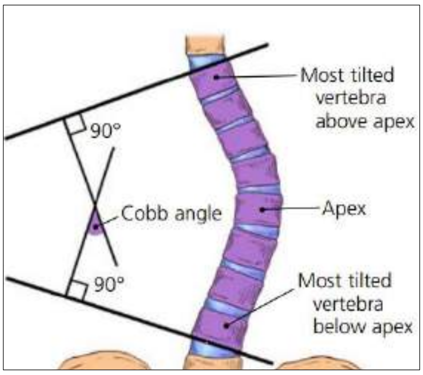
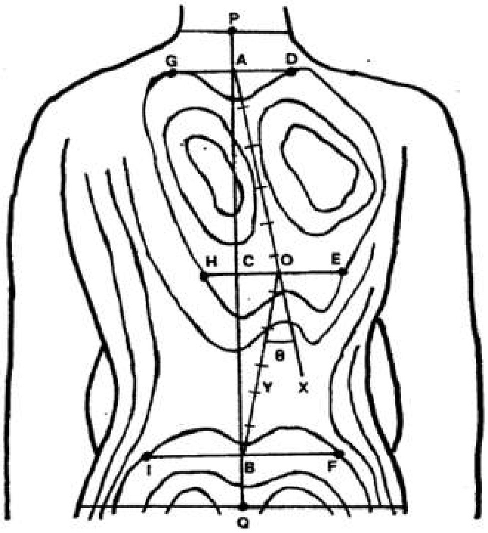


Fig. 11: Measurement of Cobb angle [143]

To the Cobb angle, the angle value of spinal curvature measured in MIs can be approximated. Fig. 12 shows the moiré and X-ray images of the same patient.

Fig. 12: Moiré and X-ray images of the same person [22]

For the evaluation of MIs, different measurement approaches can be used. To measure the 2D curve angle of a single-curve scoliotic spine, KAMAL's approach [112, 144], for example, considers points describing the most asymmetries on the back (Fig. 13). In the MI of a healthy back, the number of moiré stripes on the two sides of the spine within the same distance measured from the midline of the back are equal. The scoliotic spine does not have this symmetry [144].



$$Y_1 = \tan^{-1}\left(\frac{|d_1 - d_2|}{AC}\right) \qquad Y_2 = \tan^{-1}\left(\frac{|d_1 - d_3|}{BC}\right)$$

$$d_1 = \frac{1}{2}\,(CH + CE)$$

$$d_2 = \frac{1}{2}\,(AD + AG)$$

$$d_3 = \frac{1}{2}\,(BF + BI)$$

$$\theta = \tan^{-1}\left(\frac{|d_1 - d_2|}{AC}\right) + \tan^{-1}\left(\frac{|d_1 - d_3|}{BC}\right)$$

Fig. 13: Measuring points and mathematical relations of Kamal’s method [112]

3.2.1 Digital projection moiré imaging applied in scoliosis

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. [33] in generalized and to some extent completed form—especially by adding additional steps 1, 7, 8 and 9 (Fig. 14).

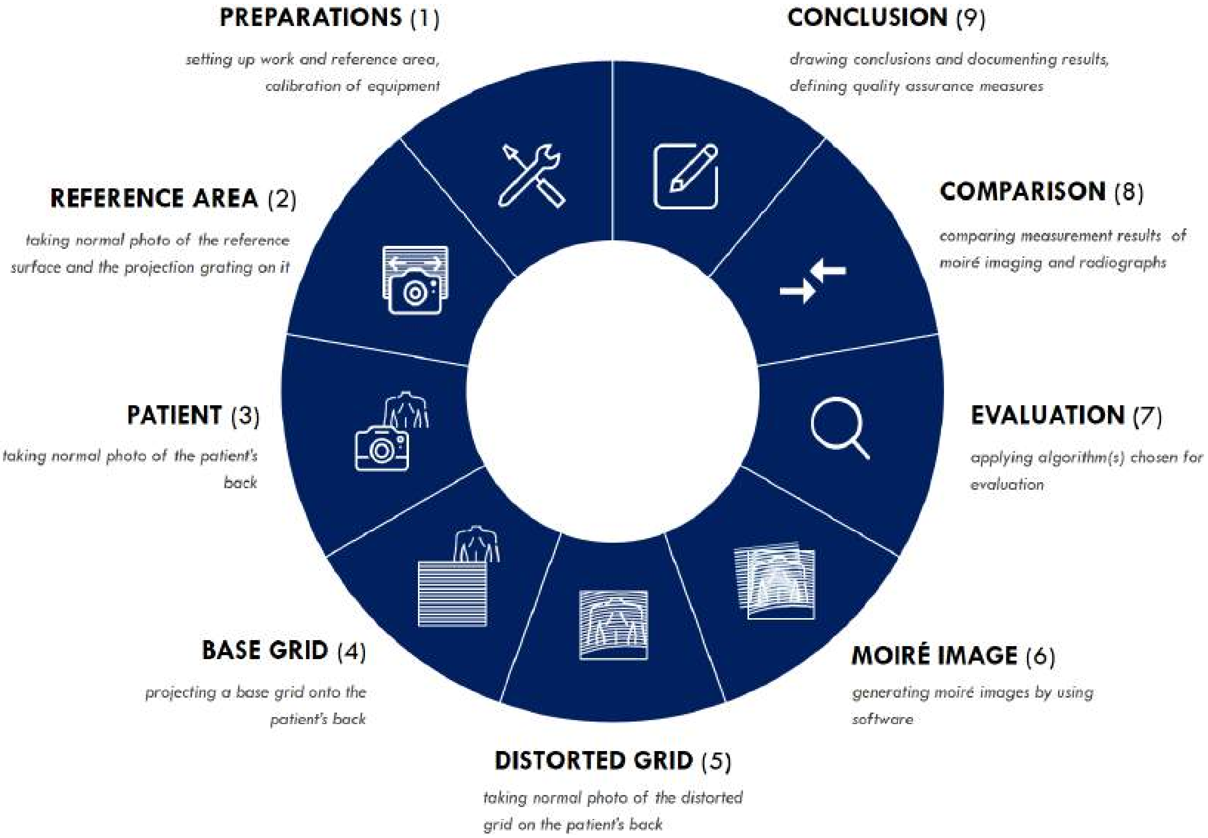


Fig. 14: Process of digital moiré imaging and examination [54].

The set of tools used for measurements is basically a classic PM equipment with the difference that the projection of the base grid is carried out with a video projector instead of a traditional one. The moiré equipment and its arrangement applied by BALLA et al. is shown in Fig.15.

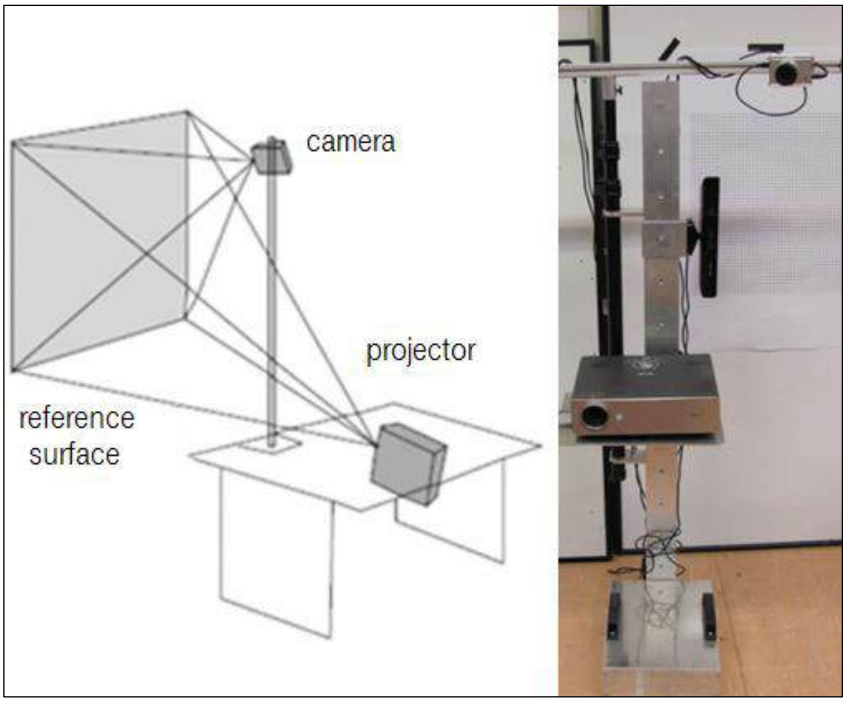


Fig. 15: Digital moiré equipment: scheme and realization (transl. by auth) [33]

The process of digital moiré imaging and examination can be summarized in 9 steps, as follows:

(1) **Preparations**…

…that includes:

- setting up the work area and reference surface
- setting up and calibrating the moiré equipment and its optical arrangement
  The camera and light source are to be positioned perpendicular to the patient's back—to avoid bias, the light source should not be placed in a peripheral area.

(2) **Taking a normal photo of the reference surface and a base structure on it**

The image of a base structure (projection grating) on the reference surface plays a role in step (6) when the moiré phenomenon is generated. To achieve the moiré phenomenon, custom image processing methods can be developed. In the moiré generation procedure, BALLA et al., for example, used XOR logic[9] (logical moiré) based on images of gratings projected onto the reference surface and the spine.

---

[9] XOR is a logical operation that outputs true only when inputs differ. XOR is also called exclusive or or exclusive disjunction.

(3) **Taking a normal digital photograph of the patient's back**

While taking the photograph the patient is in natural exhalation state topless in front of the reference surface (Fig. 16). The outcome of this step strongly depends on the posture setting applied that may easily lead to different moiré contours in MIs of the same patient (for further explanation on posture setting, see sec. 3.2.2).

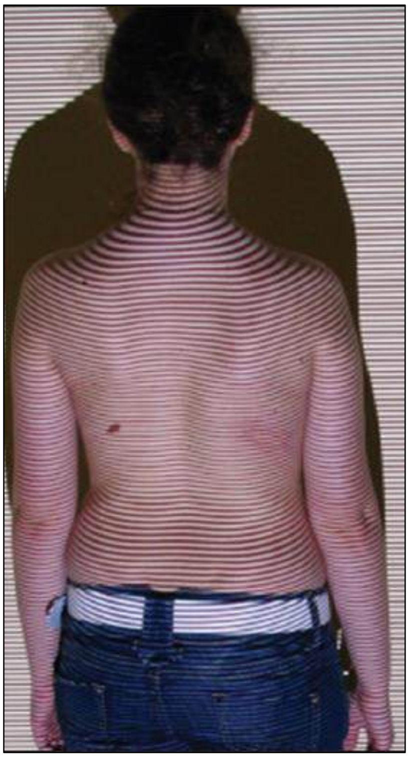



Fig. 16: Normal picture of the patient in front of the reference surface (L) [33]
Fig. 17: Linear base grid and its distortion on the human back (R) [33]

(4) **Projecting a base grid onto the patient's back**…

…as a result of which the grid is distorted in accordance with the surface characteristics of the back (Fig. 17).

(5) **Taking a normal digital photograph of the distorted grid on the patient's back**

It is to be noted that the picture thus obtained is not a MI, since it shows only a distorted linear base grid. However, moiré phenomenon may be detected in similar images when linear stripes interfere e.g. with pixels of a computer display. To overcome this effect, Fig. 17 is shown in a slightly larger size (Fig. 16 is also enlarged due to symmetrical considerations).

(6) **Generating moiré on images using software** (Fig. 18).

Let us recall what was discussed in sec. 2.2 on PMT. By using software, a reference grid can be added afterwards to an image that comprises only a base grid. In that case moiré phenomenon is produced due to the interference between the lines of software-generated and base grids. The MIs obtained that way provide valuable information about the unique topographic characteristics of the back. Examples of image processing software environments include MATLAB (Matrix Laboratory, MathWorks®) or LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench, National Instruments™).

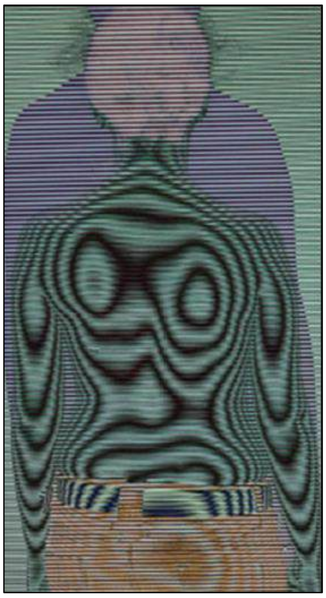


Fig. 18: Software-generated moiré image [33]

(7) **Evaluating the moiré image**

Using appropriate algorithms adapted to the measurement is a key factor in evaluating MIs. BALLA et al. followed Kamal's mathematical-geometric approach for measuring the 2D curve angle of single-curve scoliotic spines. In the evaluation procedure, it is vital to consider the same contour lines and heights so that the results of the image series of the patient are comparable.

(8) **Comparing** spinal curvature angle values obtained by moiré technique with Cobb values measured on radiographs of the same patient.

(9) **Drawing conclusions and documenting results** and experiences to improve the quality of subsequent measurements and (algorithmic) research.

Step 9 can be a conclusion of quality assurance measures to refine further measurements.

3.2.2 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 [20, 33, 121]. The moiré technique makes it possible to study large target groups in a fast, reproducible and cost-effective way [20, 21, 121]. A moiré technique chosen and algorithmized well can be convenient for substitution or as a complement of X-ray images in scoliosis [20, 121, 122]. The listed features above should be taken seriously, also in estimating its social benefits. In terms of cost-effectiveness, for example, the MM could be a feasible alternative in third world countries. However, when developing novel methods for medical diagnostics with reduced costs in mind, it is indispensable that they are proved adequate alternatives to the existing ones. For this, precision and accuracy are essential factors.

The determination of precision is based on the comparison of results from repeated measurements, while accuracy—in the design of clinical trials—is proposed to be established in relation to a “gold standard” [145]. The gold standard is a reference measurement that is carried out by a technique believed to best represent the true value of the measured property. From this already, we can presume that choosing a measurement approach designated as the gold standard can be a difficult judgement that the investigator needs to make, drawing on previous work in the field [145]. In the diagnosis of scoliosis, Cobb angle is considered as the gold standard [23, 34, 39].

The lack of methodological standardisation is another problem in the application of MT in scoliosis. Although we know a few body posture protocols [23, 33, 146] applied during moiré examinations, we cannot speak about a concrete methodology that could lead to generally reliable results. ADAIR et al. [146], for example, suggest that the patients stand erect with feet together, buttocks placed close to the screen (i.e. grid) and with shoulders parallel to it. This practice, however, may result that patient's posture is "arranged" by the evaluator—although ADAIR et al.'s results confirmed scoliotic cases in 94 percent in children aged 10-12 years [23, 146]. PORTO et al. refer to other studies that propose that patients should be in the standing position, feet apart naturally, and body as close to the grid as possible without touching it [23]. In BALLA et al. [33], we may also find indications on the importance of a standardised body posture while performing moiré imaging. They emphasised that attention must be paid to the position of the pelvic bone and to the measurement and equalization of limb length—if necessary. In these operations, they enlisted the help of physiotherapists. A methodological standard could help the better evaluation of MIs of scoliotic patients with distorted trunks where results can be misinterpreted [23, 33, 34]. For this reason, Cobb angle is still the gold standard in the diagnosis of scoliosis [39]. In general, if we want to draw conclusions about the shape of a surface from its moiré patterns, it is important that the surface be analyzed in a position that conforms to the measurement standard. This is crucial when performing medical examinations, especially in case of trunk deformations [37]. Therefore, although MT provides information about the shape of the surface examined, it is a major drawback that the conclusion drawn will not be without ambiguity [33, 34, 35]. In other respects, as well, we can find hints to the lack of standardisation when three surface topographical methods (MT, Scoliometer® and BCD) are compared. PEARSALL et al. [36] concluded that these three techniques could not be used interchangeably in clinical recording if the posture is not standardised. Therefore, the standardised posture is a problem that needs to be resolved [23, 24].

In their recent systematic review on MT, LABECKA et PLANDOWSKA [1] concluded that there is only moderate evidence for the reliability and validity of the method as a screening and diagnostic tool. Although they consider MT as an alternative method of examining the deformity of the spine and trunk but as for the accuracy of MT they identified no strong evidence. In order to use MT as an accurate screening tool—they say—the methodology of MT should be standardized.

In relation to surface topographic examinations used in the diagnostics of scoliosis and other spinal deformities, we can say that the determination of gold standard parameters still waits to be named [39]. To let the users speak the same language, the unification of surface topography parameters is an additional challenge—mainly for producers of surface topography equipment [39]. According to KOTWICKI et al. surface topography still would have a chance to work in service of patients, if additional effort to standardise the examination is made [39].

Based on the study of collected literature, however, only a need for standardisation but not a serious effort to invest can be seen. PORTO et al. point out that it is easy to notice in the scientific literature that there are more studies relating to the application of MT than those that focus on the accuracy of the method itself and the standardisation of the measurements obtained [23]. They note that there was no standardisation in this aspect found in the literature. Considering this methodological deficit—as LABECKA et PLANDOWSKA warn [1]—researchers should be careful in drawing conclusions from studies using the MT measurement.

The amount of labour required for the evaluation of MIs is not inconsiderable [23, 27]. Some researchers see the best solution for that in an automatic system [21, 22, 23, 24, 25, 26]. 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 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 [30]. Beyond, but in parallel to the technical-biomedical and medical knowledge, the continuous and conscious presence of the human factor plays a key role that has a significant influence on communication processes among interdisciplinary research groups [53].

3.3 Conclusion and Further Thoughts

In the topographical analysis of the human body, MT is able to indirectly identify areas with structural deformities under the skin through the form of the body surface. This makes the importance of R&D of MT in a clinical setting particularly justified. MT allows non-invasive, non-ionizing and cost-effective measurements with an unlimited number of repetitions. From the 1980s, moiré surface analyses were conducted on the whole human body, including the oral cavity, bones, teeth and the skeletal system. In medical technical applications, for the visualization of moiré contours, both the SMT and PMT are used. With the development of image processing, however, from the 2000s, the latter appears more common in postural topographies. The general characteristicsof MT, that the contours on the same patient strongly depend on the posture setting applied, despite all its advantages, may easily bias the outcome of medical evaluations. The lack of methodological standardisation in body posture is another problem not just in MT, but in other surface topographical methods in scoliosis. This circumstance must be borne in mind in considering MT as an adequate alternative to existing diagnostics methods. An even more significant problem than the previous ones is that only a need for standardisation but not a serious effort to invest can be seen in research studies. In the light of these problems, the high amount of labour required for the evaluation of MIs becomes especially important to be resolved. To achieve this, a user-friendly system, where image processing challenges can be handled and diagnostic methodologies can be flexibly tested, may be suitable.

4 A Research Framework Concept for Producing, Processing and Analysing Moiré Images of Scoliotic Spines Based on Manual/Semi-automated Solutions

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 [21, 22, 23, 24, 25, 26]—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 [23]. Non-continuous fringes are generated by non-continuous surfaces that make subjective analysis very difficult [147]. In these cases, errors of evaluation also occur when software is used to analyse moiré topograms [23]. Thus, implementing a fully automated image analysis is challenging. Another reason for this is down to the complexity of fringe patterns and the condition that processing of MIs require several unique solutions that are influenced by the given optical arrangement, intensity distribution resulting from illumination applied, nature of noise and detection [27, 28, 29]. For reducing uncertainties in moiré pattern analysis, an accurate segmentation of MFs is needed [148].

Keeping in mind the circumstances described above, the concept and idea of the Moiré Imaging Tool for Scoliosis (MITS) was induced by the author's personal demand on having opportunities for exploratory mathematical-geometric calculations performed on MIs of scoliotic spines, and the condition that no tool with similar features and complexity—as described in sec. 4.1—was identified during the study (also remember sec. 1.2.2 Theses 2-4). The base functions of MITS can be divided into three parts: (a) Fringe Segmentation Tool, (b) Contour Analysis Tool, (c) Moiré Production Tool. Guiding aspects to be considered in developing UI incorporating (a-c) are also summarized.

The concept of base functions, UI and SWOT-analysis of MITS is introduced in sec. 4.1, while MF segmenting algorithms using filtering and morphological operations as a possible feature of (a) is presented in sec. 5.

Please note that the concept of MITS and its UI illustrations does not represent the final version of the targeted solution. The project/concept is under development. UI illustrations for each sub-tool of MITS are drawn in WireframeSketcher.

4.1 The concept of Moiré Imaging Tool for Scoliosis (MITS)

MITS is meant to be 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 essence of 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 feasible and realistic answers to challenges caused by problems of manual and automated MI processing and evaluating.

Specific aims of MITS with respect to generating, processing and analysing MIs of scoliotic spines are as follows:

(1) **To segment MFs in QRT** by applying manual adjustable morphological operations and built-in algorithms to support moiré pattern evaluation—**Fringe Segmentation Tool**.

(2) **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**.

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

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. In sec. 4.1.1.2, a solution of the Fringe Segmentation Tool of MITS will be presented as a prototype developed by the author in MATLAB environment.

4.1.1 Fringe Segmentation Tool

The planned function of the Fringe Segmentation Tool (FST) is meant to support delineation and contouring of MFs in QRT by applying manual adjustable morphological operations and built-in algorithms based on pre-defined sequences. Beyond conceptualization, for prototyping purposes, FST of MITS has been programmed by the author in MATLAB environment. In the following subsections, the concept (sec. 4.1.1.1) and the prototype (sec. 4.1.1.2) of FST are separately introduced.

4.1.1.1 The Concept of Fringe Segmentation Tool

The key elements of FST are (1) field of morphological operations, (2) panel for previewing processing phases and (3) standard buttons (Fig. 19, enlarged in Appendix A).

(1) Field of morphological operations

Field of morphological operations comprises labels and settings for morphological image processing adapted to QRT adjustments on images loaded in the program. Base package of morphological operations is to be implemented to adjust brightness, contrast, thresholding, and to apply filters as dilation, 2-D Gaussian blur and skeletonization. Most of the field is covered by adjustable parameters related to and defined by morphological operations. The field contains a dedicated button for transferring settings to other images.

(2) Button bar for activating built-in contouring algorithms

The aim of built-in contouring algorithms is to support manual image processing by providing pre-defined automated sequences of morphological operations for segmenting the MFs of scoliotic spines. These algorithms are to be developed by studying and applying segmentation methods adapted to MIs from various sources. In sec. 5, practical examples of MF segmenting algorithms using only filtering and morphological operations are presented.

For that purpose, a database of MIs is to be built up. For the time being, SALUS Ortopédtechnika Kft. is the only partner contacted to support this research by providing MIs. The involvement of other research institutes is under planning.

(3) Panel for previewing processing phases

The panel for previewing serves as a detachable frame for QRT visualisation of MIs being processed. Preview includes five phases of image processing that results (a) original MI in grayscale, (b) pre-filtered (i.e. thresholded) image with thick fringe contours, (c) skeletonized moiré contours and its overlays with both (d) pre-filtered and (e) original’s grayscale images. The panel also supports full-screen mode of selected images and includes buttons for both Moiré Production Tool (MPT) and Contour Analysis Tool (CAT).

(4) Standard buttons

Standard buttons are present in all sub-tools of MITS for executing tasks, such as loading/unloading/exporting images, resetting parameters and closing program.

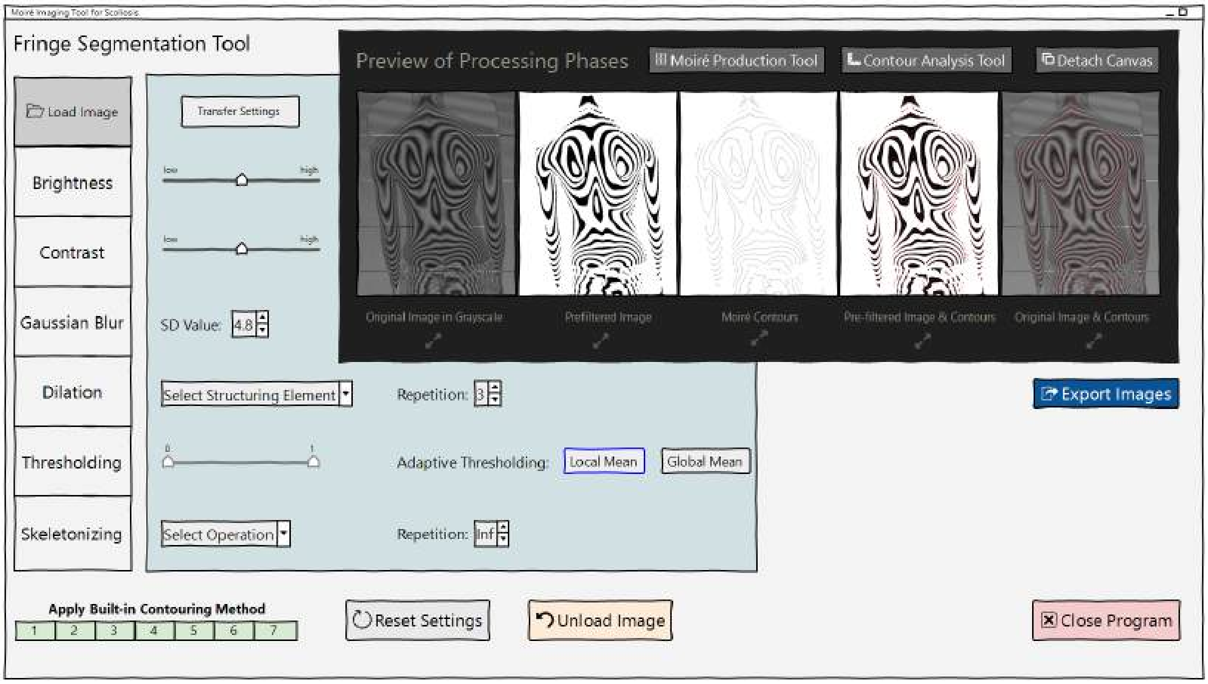


Fig. 19: Concept preview of Fringe Segmentation Tool.
(Enlarged in Appendix A)

4.1.1.2 The Prototype of Fringe Segmentation Tool

For a practical illustration of the proposed FST, an application is developed in MATLAB App Designer (R2018B) [149]. The logical layout and the structure of the application is designed by following the image processing steps with the exclusion of dilation[10] of the proposed segmenting algorithm introduced in sec. 5.1. For the design of the graphic user interface (GUI), guiding aspects summarized in sec. 4.1.4 were considered.

4.1.1.2.1 The Graphic User Interface

The GUI of the FST consists of four main areas: (1) image canvases for original reference and processed image, (2) image processing toolbar, (3) toolbar for displaying skeletonized results and (4) built-in automatic segmenting algorithms (Fig. 20).

---

[10] Dilation is not a requirement for a simple illustration of FST. However, for a precise segmentation, dilation may represent an important factor in image processing—as it is introduced in sec. 5.1—by gradually enlarging the boundaries of regions of foreground pixels.

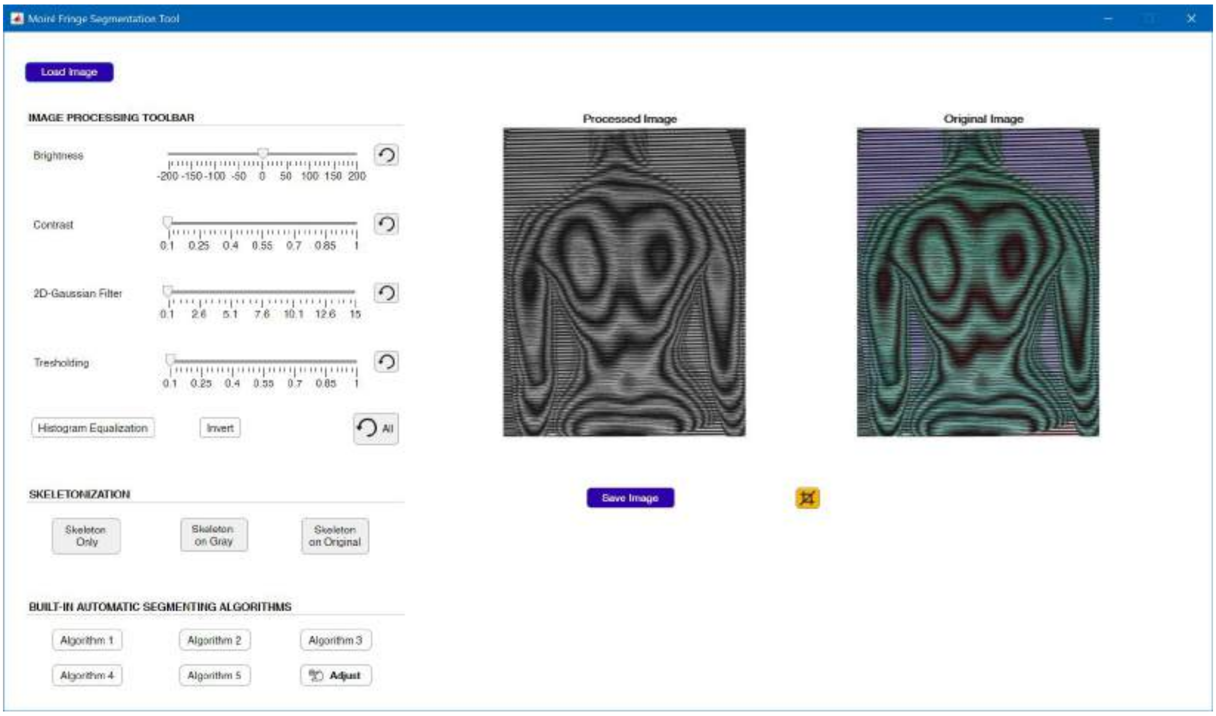


Fig. 20: The main screen of the prototype of the Fringe Segmenting Tool

(1) Image canvases

On the right side of the application GUI two image canvases are positioned: one for reference ("Original Image" on the right side) and another for displaying the results of QRT image processing ("Processed Image" in the middle). During manipulations via the image processing toolbar (to the left of the canvases), the canvas "Processed Image" supporting an accurate segmentation of the original's grayscale shows the processing phases in QRT. In order to minimize data loss during image manipulations, the canvas "Original Image" shows the original input image during the whole processing phase constantly. By using the dedicated crop button ⌗ below the middle of the canvases, rectangular selection of region of interest (ROI) on input images can be performed.

(2) Image processing toolbar

The image processing toolbar of the prototype provides QRT filtering and morphological adjustments on images loaded in the program ("Load Image" button in the upper left corner). In the FST demo, seven image processing operations are implemented: (1) brightness, (2) contrast, (3) 2-D Gaussian filter, (4) thresholding, (5) histogram equalization, (6) image inversion, and (7) skeletonization. Adjustable horizontal scales with reset button ↺ for operations (1-4) and dedicated buttons for operations (5-7) are implemented. Both solutions provide QRT visualization on the canvas "Processed Image". For resetting all image modifications, reset all button ↺ All is also implemented. Since there are more options implemented for visualizing skeletonization that is the last step in the proposed segmenting solution, buttons for skeletonization are displayed under the image processing toolbar separately. These buttons display results by visualizing skeletonized MFs in the context of (a) skeleton only, (b) original's grayscale image, (c) original image. Image processing results can be exported via the button "Save Image" in the following formats: (1) Windows Bitmap (.bmp), (2) JPEG 2000 (raw codestream, .j2c, .j2k), (3) JPEG 2000 (Part 1, .jp2), (4) Joint Photographic Experts Group (.jpg, .jpeg), (5) Portable Bitmap (.pbm), (6) Portable Graymap (.pgm), (7) Portable Network Graphics (.png), (8) Portable Pixmap (.ppm), (9) Sun Raster (.ras), (10) Tagged Image File Format (.tif, .tiff).

(3) Built-in automatic segmenting algorithms

Built-in contouring algorithms are meant to support manual image segmentation by predefined automated sequences of morphological operations. In the FST demo, three algorithms are implemented (button "Algorithm 1-3") that automatically follow the segmenting procedure introduced in sec. 5.1. ("Algorithm 1"), sec. 5.2 ("Algorithm 3"). Button for "Algorithm 2" follows a segmenting method that is currently being under development. Buttons for "Algorithm 4-5" are placeholders for further automatic algorithms to be developed in future research. For fine-tuning the results of automatic algorithms, manual adjustments can be performed up to the thresholding phase of image processing by using the button "Adjust" Adjust.

The operation of the prototype of the FST is demonstrated in Digital Appendix C.

4.1.1.2.2 Conclusion

The prototype application for fringe segmentation allows a dynamically changeable and user-friendly processing configuration on MIs created with XOR logic. The application-supported segmenting method is simple, fast to process and, for the most part of the images follows the moiré stripes accurately. Although the solution used in the prototype includes a relatively narrow set of image filtering and processing operations, it still allows for a visually traceable and relatively accurate segmentation that may even be used for specific measurements. Due to its simplicity and fast operation, an improved solution to the segmenting tool could also replace time demanding and complex segmentation methods. 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. A possible way for improving the fringe segmenting application is to extend its functions with further 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 [148] for combining the manual and pre-defined automatic algorithms, (6) deep learning algorithms for automatic segmenting algorithms (a high amount of sample data required).

4.1.2 Contour Analysis Tool

CAT is to be implemented in FST as a measurement function for analysing moiré contours and their mathematical-geometric relations in order to identify methods for calculating spinal curvature angle values approximated to Cobb angles. In terms of measurement, the concept of CAT supports both concrete preliminary ideas and exploratory approaches. The key elements of CAT are (1) measuring functions, (2) button bar for automated calculations, (3) panel for image and object selection, (4) Cobb angle calculator, and (5) standard buttons (Fig. 21, enlarged in Appendix B).

(1) Measuring functions

The base measuring functions cover calculations on MIs such as area and circumference of MFs and its largest asymmetries relative to the midline of the back, and angle values between its arbitrarily selected points. The aim of these measurement parameters is to identify relations between MIs and spinal curvature values—let it be an exploratory or pre-defined method-based approach (for example, KAMAL'S method).

(2) Button bar for automated calculations

The button bar for automated calculations is meant to execute built-in algorithms for calculating spinal curvature angle values based on different methods. Current plans include the incorporation of KAMAL'S method discussed above. Further approaches for calculating spinal angle values on MIs are to be systematically explored and evaluated in terms of feasibility in a later, postdoctoral phase of the research.

(3) Panel for image and object selection

The panel for image and object selection similar to FST(3) works as a detachable frame for selecting and measuring objects and points on (a) skeletonized moiré contours and its overlays with both (b) pre-filtered and (c) original's grayscale images, and optionally for (d) radiographs. Latter serves as a reference in measurements performed on MIs. Panel options cover full-screen mode of selected images.

(4) Cobb angle calculator

For an evidence-based research, a manual Cobb angle calculator provides a possibility of determining Cobb values on radiographs and comparing their results to values measured on MIs.

(5) Standard buttons

The same as in point (4) in the concept of FST (sec. 4.1.1.1).

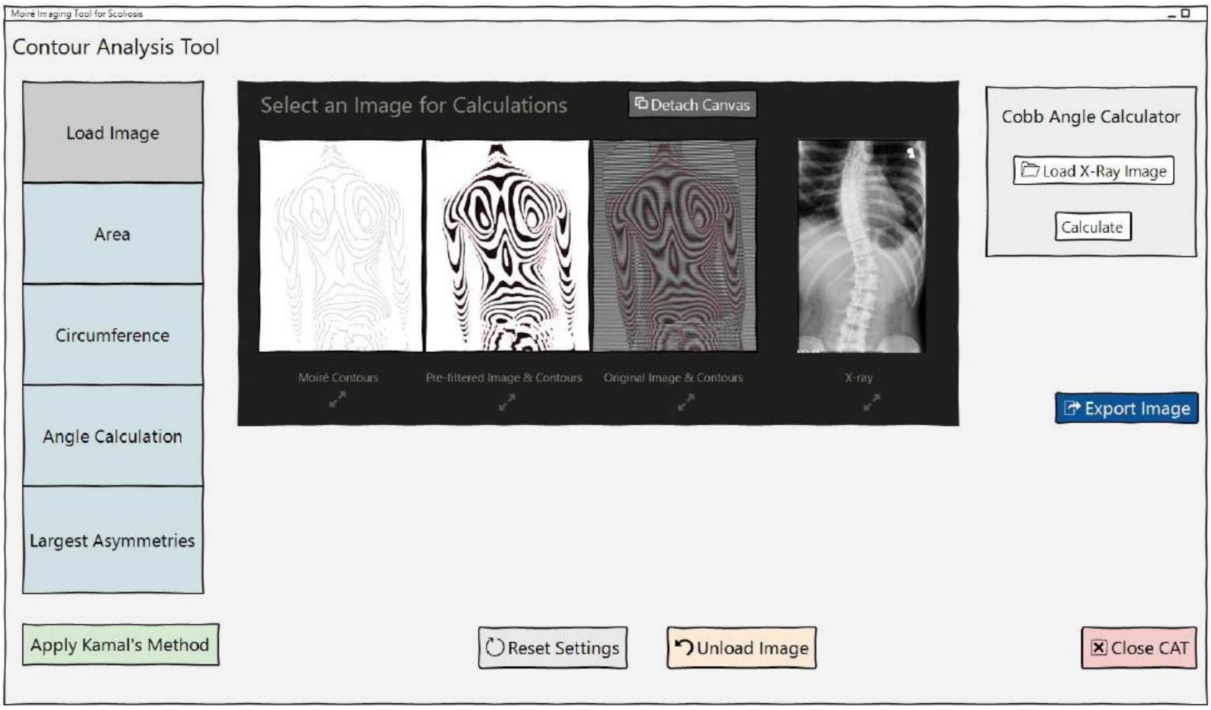


Fig. 21: Concept preview of Contour Analysis Tool
(Enlarged in Appendix B)

4.1.3 *Moiré Production Tool*

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 (Fig. 22, enlarged in Appendix C).

(1) Field of selectable geometries and their transformation options

With selectable geometries and their transformation options users can generate moiré phenomenon on input images made by (digital) projection technique. Following the concept of

PMT applied in scoliosis, the base geometry consists of equidistant lines only. For supporting research experiments, further geometries such as triangles, circles, random pixels and checkerboard patterns are to be implemented in MPT. Transformations for conforming geometries to input images are planned to be applied so that rotation, translation and scaling of overlaying structures is adapted to input images. By providing the possibility of exporting custom geometries only, users can use the same pattern for projection grid and reference grid while performing moiré imaging.

(2) Panel for image and overlaying geometry

The detachable panel gives the frame for previewing input images and geometries selected to be overlaid. Full-screen mode of preview is supported.

(3) Standard buttons.

The same as in point (4) in the concept of FST (sec. 4.1.1.1).

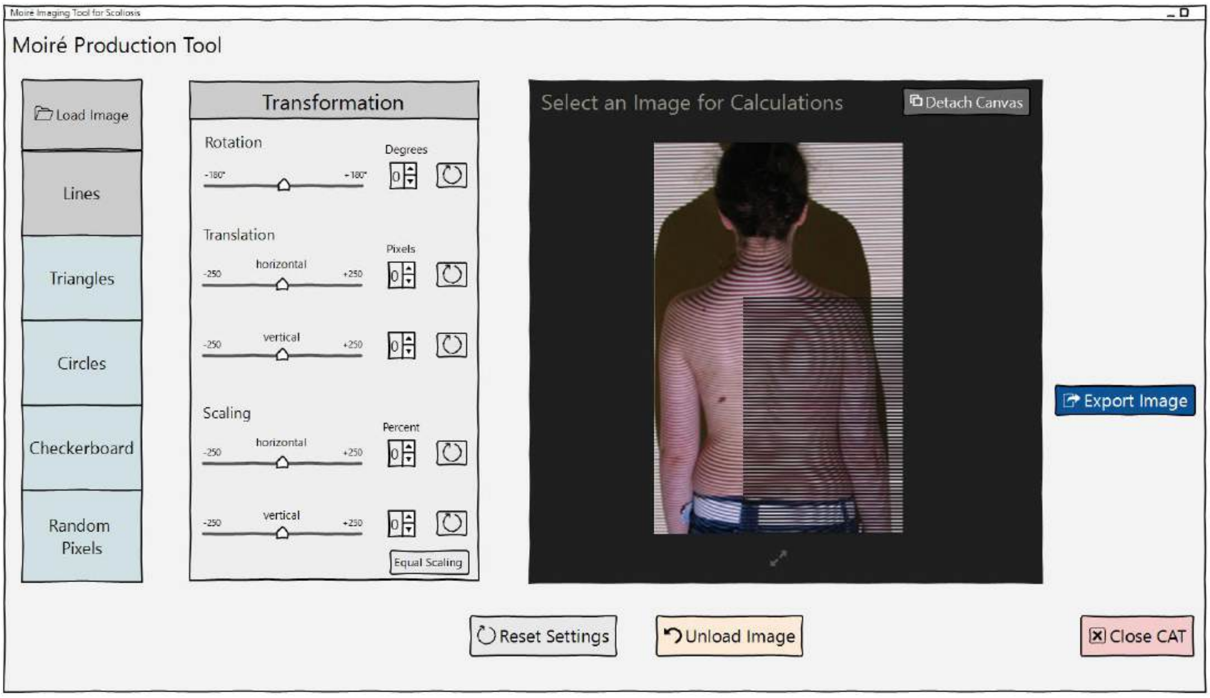


Fig. 22: Concept preview of Moiré Production Tool
(Enlarged in Appendix C)

4.1.4 Guiding Aspects for User Interface Design of MITS

Healthcare and medical research related information and data can be complex to understand and communicate. User interfaces often have superficial design problems that have negative effects on product usability and appeal [52]. One of the most critical aspects of a well-designed application is how the data are displayed and accessed [150]. Displaying relevant information efficiently and comprehensively is a challenge, also for the most experienced (G)UI developer. Companies dealing with medical devices often spend several months developing a preliminary UI design only.

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. Guiding aspects to be considered in developing UI design for medical/healthcare applications are summarized below (1-11), based on practical suggestions for medical device interfaces [52] and healthcare applications [150].

(1) Reducing screen density

Empty spaces of UI play an important role in separating information into related groups and providing a resting place for the user's eye. Dense-looking interfaces make difficult to identify specific information at a glance. Nonessential and extraneous information can be eliminated by design considerations, as follows [52]:

- Applying pop-ups or relocation (to other screens) for secondary information
- Reducing graphic elements associated with brand identity, such as logos and brand names
- Using simpler graphics, e.g. silhouette-styled icons instead of 3D illustrations
- Separating content by empty spaces instead of lines
- Reducing text by stating things more simply

(2) Providing navigation cues and options

Ambiguously designed navigation cues may cause users losing themselves in the UI structure. Placing meaningful titles on each screen and subcomponent by means of a contrasting horizontal bar with text is helpful. Grouping navigation options and controls together in a single consistent location without triggering users' fear of getting lost or causing irreparable harm is recommended [52]. Minimizing the load on users by providing informative feedback, memory aids and other cognitive supports is considered as also essential. The latter requires making real assumptions on the target user population based on preliminary user-related knowledge.

(3) Ascribing to a grid

Due to their less complexity, aligned on-screen elements can improve visual appeal and perceived simplicity. Finding information by scanning a straight path is quicker for the human eye than following irregular or discontinuous structures. The predictability of position of grid-based visual elements makes the implementation of computer codes more efficient. Defining the dominant components of the screen and approximating space requirements is proposed to be the first step in developing grid-based content. For example, space may be allotted for a window title, title bar in the software, menu area, body of content and a prompt by dividing the screen vertically into four bands that are 1/16, 2/16, 12/16 and 1/16 the height of the screen (Fig. 23 and 24) [13]. Margins around the grid lines can support visual appeal by keeping on-screen elements at a fixed distance from the grid lines. An effective GUI, beyond well-designed graphics, represents a pleasing arrangement of graphical elements on the screen. For understanding the users' points of view better and developing a screen layout that guides the user experience and promotes an intuitive usability, involvement of a dedicated GUI developer is recommended [52].

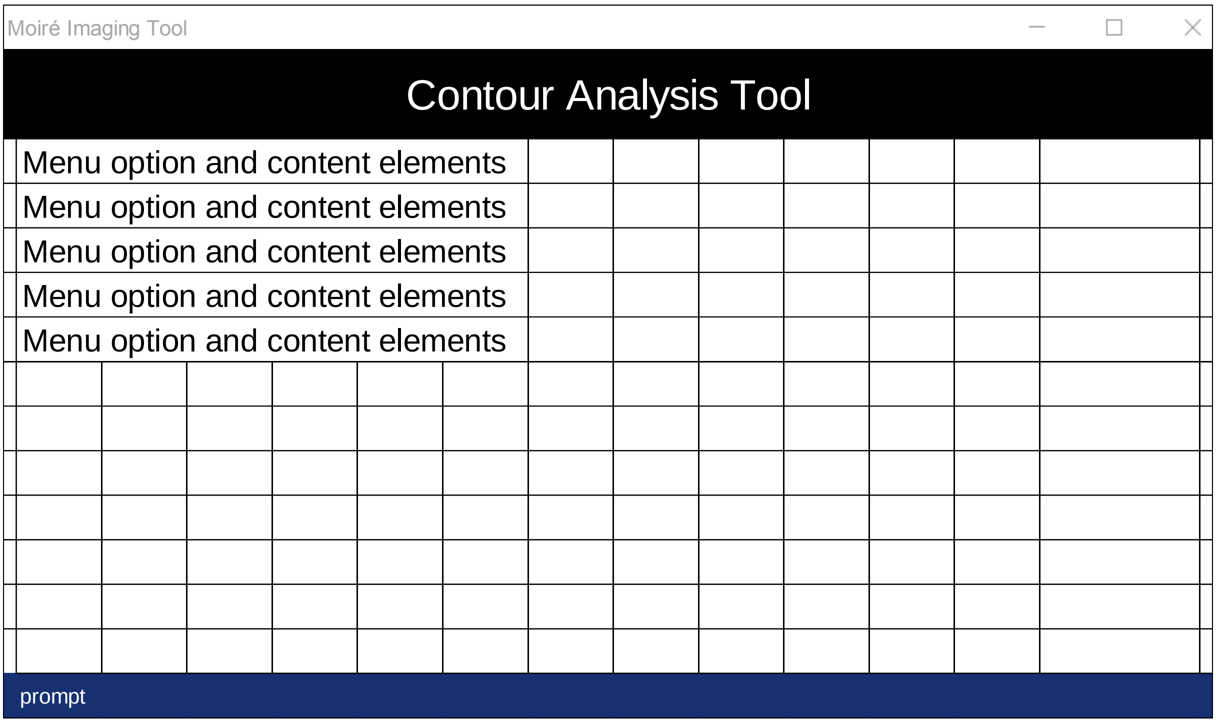


Fig. 23: A possible solution of a grid-based screen (with grids drawn).

(4) Creating visual balance

By creating visual balance or symmetry, each side of the screen has about the same amount of content as empty space so that elements neither appear askew, nor seem to be missing. It is especially important about the vertical axis. Perfect symmetry, however, may appear tedious for some users, so virtually inevitable and slight imbalances may also create a comfortable visual effect [52].

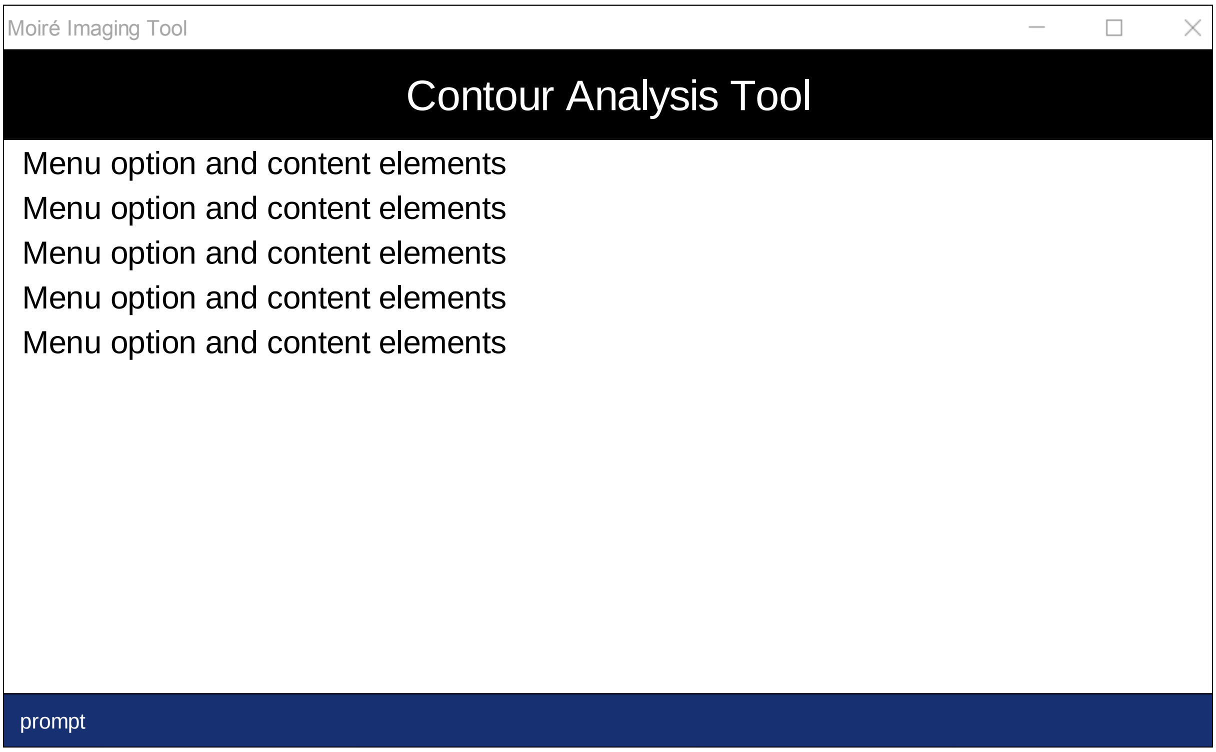


Fig. 24: A possible solution of a grid-based screen (without grids drawn)

(5) Limiting the number of colors

Experienced user designers suggest limiting the number of colours used in the UI. Accordingly, screen components should be kept to between 3 and 5 colours including the shades of gray. Special and small-scale elements may be coloured by additional hues. In terms of medical application colours are proposed to be selected in consistency with medical conventions (e.g. using red refers to alarm information) [52].

(6) Simplifying typography

Typographical rules have significant influence on an easy-to-read screen by steering end users toward prioritized content. For a harmonic visual contrast, UI designers generally commit one single font in just a few character sizes such as 12-, 18-, and 24-point type (Table 4). Simplifying typography can be achieved by eliminating excessive highlighting such as underlining, **bolding** and *italicizing* [52].

(7) Using hierarchical labels

Redundancy in labelling easily causes congested screens that requires longer time to read through. Hierarchical labelling displays information more efficiently and can save space and time at scanning screen content (Table 5 and 6).

Table 4: Hierarchy of font sizes proposed by WIKLUND[52]

Font Size [points]	Sample Content
24	Generate Moiré Pattern
18	Selected Geometry: line
12	Degree of rotation: 7° Vertical translation: +150 px Horizontal translation: -40 px Horizontal scaling: +30 px Vertical scaling: 0 px

Table 5: An example for redundant labelling in context of MPT

Rotation	7°
Horizontal Translation	+150 px
Vertical Translation	-30 px
Horizontal Scaling	+30 px
Horizontal Scaling	0 px
Vertical Scaling	0 px

Table 6: An example for hierarchical labelling in context of MPT

	Horizontal [px]	Vertical [px]	Degree [°]
Rotation	-	-	7
Translation	+150	-30	-
Scaling	+30	0	-

(8) Using simple language

Writing in a technical manner and using complex words and phrases in UI can undermine a user-friendly software environment. Finding solutions to word things simpler but without oversimplifying the UI is vital. Specific corrective measures include [52, 150]:

- writing shorter sentences (½-2 lines) and paragraphs (2-3 sentences)
- breaking complex procedures into ordered steps
- using meaningful headings and subheadings
- following consistent syntax

- using clear and concise text in the user's language

(9) Refining and harmonizing icons

Ideally, icons of any consumer, business and medical applications are highly refined and tested. Even a limited investment in icon quality and comprehension by applying talented designers may lead to a disproportionately large payoff. To design a uniform concept and maximized comprehension to icons, we can take the following steps [52]:

- Developing a limited set of icon elements that represent nouns, e.g. linear grating, patient.
- Accentuate the most significant aspects of the object or action by simplifying and eliminating unnecessary and potentially confusing icon elements.
- Designing similar-purpose icons to the same style, form and overall size, e.g. a 2D rectangle icon with 64 x 64 px or a 3D circular icon with 32 x 32 px
- Applying user testing to gain feedback on icon comprehension.
- Reinforcing icons with text labels or hints that appear when the icon is selected or highlighted.

(10) Eliminating inconsistencies

Inconsistencies in UI have especially a negative effect on usability. Many factors are to be preserved consistently in UI such as labelling, terminology, graphic conventions, components, layout. For example, using red colour to communicate both critical and noncritical information or communicating basic functions with words like 'enter', 'select', 'OK', '*continue'* may be annoying and confusing [52, 150]. Such inconsistencies in design can be avoided by creating and following a style guide. Following WIKLUND's recommendation [52], in the MITS project an organized collection of notes and rules will be created by Q1 2024 (exp).

(11) Following common best-practice standards

There are many standards and guidelines for terminology, abbreviations, interactions etc. Standards ensure professional quality while reducing the design effort; therefore, they are essential for cross-application consistency and effective implementation. Galitz in his exhaustive work on UIs provides a detailed guidance interface and screen design from the user's perspective [151].

4.1.5 SWOT analysis of MITS in the Context of the Moiré Method

In designing products and services, SWOT analysis is often used for measuring the vitality of a product or project. The analysis is based on four success determinant factors: the internal factors as strengths (S) and weaknesses (W) and the external circumstances as opportunities (O) and threats (T). Strengths and weaknesses refer to elements being under control of the project or are determined by the object's nature. External forces influence and affect every organization or working group and their members.

In the current phase of research, the strategic planning tool SWOT analysis is considered as a reasonable technique to use. The aim of the SWOT analysis is to have a summarized overview of the viability of MM and the concept of MITS for medical research in terms of scientific, financial and technical aspects (Table 7-10).

The basic strengths of the MM are that it is simple, fast to operate, and it makes data acquisition in QRT possible. MT is flexible, and it allows the study of both static and dynamic events repeatedly with adaptable parameters and variable resolution. MT exerts no pressure on the body, and it is non-invasive and uses no harmful ionizing radiation that may violate political, religious and other beliefs or ethical issues while imaging. The equipment required to MT is easily accessible, relatively inexpensive and portable.

As for the strengths of MITS—after implementing its concept along with FST, CAT and MPT—multifunctional (3 in 1) experimental moiré research adapted to scoliosis becomes possible in QRT. In MITS, the study of MIs of the human spine can be supported by automatic fringe segmenting and evaluating algorithms. The location- and time-independent and flexible experimental research in MITS can play an accelerating role in defining standardized body posture for moiré imaging. Also, working hours of medical professionals can be reduced by the fast operating research tool of MITS. The use of the software requires no special training—it is to be designed for intuitive experimental research. The software is to be released as an inexpensive and widely accessible tool with low system requirements (business model is under development).

Table 7: SWOT analysis of MITS in context of the moiré method: STRENGTHS

<table>
<tr><th colspan="3">STRENGTHS</th></tr>
<tr><td colspan="3">Moiré method</td></tr>
<tr><td colspan="3">▪ 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)</td></tr>
<tr><td colspan="3">Moiré Imaging Tool for Scoliosis (MITS)</td></tr>
<tr><td colspan="3">▪ 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</td></tr>
<tr><td>SCIENTIFIC ASPECTS</td><td>TECHNICAL ASPECTS</td><td>FINANCIAL ASPECTS</td></tr>
</table>

A rather general weakening factor in surface topographic examinations of the human spine is the lack of standard in body posture and gold standard parameters that may lead to false or inconsequent results. Likewise, the sensitivity of MT to layout and geometry of the measurement can also be classified as a weakness of the method. Moreover, for properly produced MIs, a thorough surface analysis necessitates serious considerations and post-processing. Especially when it comes to increased resolution that may encounter technological limitations, or can only be achieved at the expense of other metrologically relevant features. The achievement of high contrast in MT and examination of high-slope surfaces are also problematic. These weaknesses, of course, affect the concept of MITS, especially in the areas of post-processing, segmentation and evaluation of MIs.

Table 8: SWOT analysis of MITS in context of the moiré method: 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	-

In the diagnostics of scoliosis, it is a serious threat for the general applicability of MT that only a need for a standardised body posture but not a widely targeted effort to invest could be identified. Communication problems between medical and engineering professionals, as we already referred to, may lead to mis-calibrations of moiré equipment and false and/or misinterpreted results. Geographical distances between researchers carry the danger of logistic and communication issues. The lack of knowledge and misuse of collaboration tools and methods in research groups may also lead to incorrect assessment of MT to the detriment of those who intend to initiate moiré research. Therefore, an incomplete or insufficient manual for the use of MT itself may cause serious damages to research. The absence or delay of investors and financial support jeopardizes moiré research.

As for the threats on MITS, no extensive testing before release and incomplete or insufficient implementation can also undermine the success of the software and the interest in moiré research. These threats include non-intuitive, complicated and user-unfriendly factors and insufficient manuals that lead to slow and inconvenient operation, and therefore, to a hindered research. Problems of reaching the target audience are also a barrier to moiré research, and need to be prevented by adequate communication strategy based on thorough research of the target group(s). Adequate data protection is also an important factor when it comes to threats—and to be addressed by targeted security features in the product development.

Table 9: SWOT analysis of MITS in context of the moiré method: 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

A significant opportunity of the MT applied in scoliosis is that it may be suitable to complement or at least substitute X-ray imaging. In achieving this, experimental research provided by the implemented concept of MITS carries the scientific and innovation potential that may be required to standard body posture protocols. By building digital databases (big data) from the results in combination with machine learning, improved or newly developed evaluating algorithms can foster biomedical research. Since MT and MITS do not depend on local technologies, the method and software can be used anywhere in the world for research.

Table 10: SWOT analysis of MITS in context of the moiré method: 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

4.2 Conclusions and Further Plans

In MT, the high amount of labour intensity in evaluating procedures and possible ambiguous conclusions in the determination of spinal curvature angle values require valid answers. Although a fully automated image analysis is considered as a possible solution in compensating labour intensity, its implementation is rather a challenging task. In this study—partially addressing this challenge—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 before mentioned image processing and evaluating challenges. For practical illustration of the fringe segmenting function of the MITS concept, an application is developed in MATLAB environment. The prototype allows for a relatively accurate manual and automatic segmentation with visually traceable results that may even be used for specific measurements. An improved solution to the software could also replace time demanding and complex segmentation methods. 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 conducted in scientific, financial, and technical aspects. Depending on the progress of the MITS project, at a later stage of the research SOAR analysis is planned to be conducted for evaluating the product (i.e. moiré equipment[11] and software with image evaluation algorithms) and its innovation potential with well-defined KPIs by eliminating the deficit-based approach of the SWOT analysis [152].

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 [153]. 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 [154]. In addition to data collection, CS enables citizens to formulate scientific questions and even answers, and to share their data with the scientific community. In the case of MITS, the target population of citizens is expected to be made up of

---

[11] Depending on the development possibilities, the MITS concept is open to develop a projection moiré equipment (hardware) in addition to the software.

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. The extracted data make it possible to trace the methods and preferences of the users—especially with regard to the sequence of the segmentation processes, mouse movements and the times allocated for each operation. In this way, a considerable amount of data can also be collected on the user experience and possible operational abnormalities (software bugs). 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 [155]. 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.

The final functions of the proposed research framework will be designed based on collected end-user feedback in the beta release of the software.

5 Segmenting Moiré Fringes of Scoliotic Spines

For reducing uncertainties in moiré pattern analysis, an accurate segmentation of MFs is vital. The segmenting algorithms introduced in this section were developed in MATLAB version 9.5.0.944444 (R2018b)[149] based on exploratory sequences and observations performed on 11 MIs made available by SALUS Ortopédtechnika Kft. Original MIs were software-generated applying digital PMT, and have a resolution of 2448 x 3264 px in 10 cases and 2736 x 3648 px in 1 single case with a bit depth of 24 and DPI of 96. MIs show patients in standing position facing the reference wall, and non-ROI areas that typically contain irrelevant image content of residual grating and non-moiré parts outside the back region. The procedure of image processing involves two main phases: (1) preprocessing MIs, (2) segmenting MFs using a sequence of filtering and morphological operations with static (sec. 5.1) and adaptive (sec. 5.2) function parameters.

The static segmentation algorithm was published as the first phase of this research [156].

5.1 Moiré Fringe Segmentation by Static Function Parameters

Based on the operation parameters applied in phase (2), two MI groups (G1, G2) are distinguished. For MIs in G1, identical parameters of processing phases result the similar outcome. For G2, different parameters are required for similar results, even in the group itself (Table 11). The reason for this is to be found in different image characteristics in terms of contrast, noise and moiré blur/confluence that are likely to result from dissimilar measurement setups. The phases of the code are illustrated in MI no. 2 of G1 (Figs. 25-35). For the other images, only the result of the segmentation is given in the overlap with grayscale ROIs (Figs. 44, 46, 48, 50, 52, 54).

5.1.1 Preprocessing Moiré Images

In the first phase of image processing, original MIs are prepared for further processing by (a) manual selection of ROIs and (b) conversion into grayscale. As a result of these steps, input images for phase 2 are obtained. Selection of ROIs is performed by rectangular cropping using *imcrop* function. Original images are reduced in size based on selected ROI area with boundaries from the neck to the hip; and from the left upper arm to the right one (Fig. 25). Cropped images vary in size according to the size of specific ROI area and patient setup (distance from the camera). The resolutions of cropped images are between the range of 784x1044 px and 1136x1406 px.

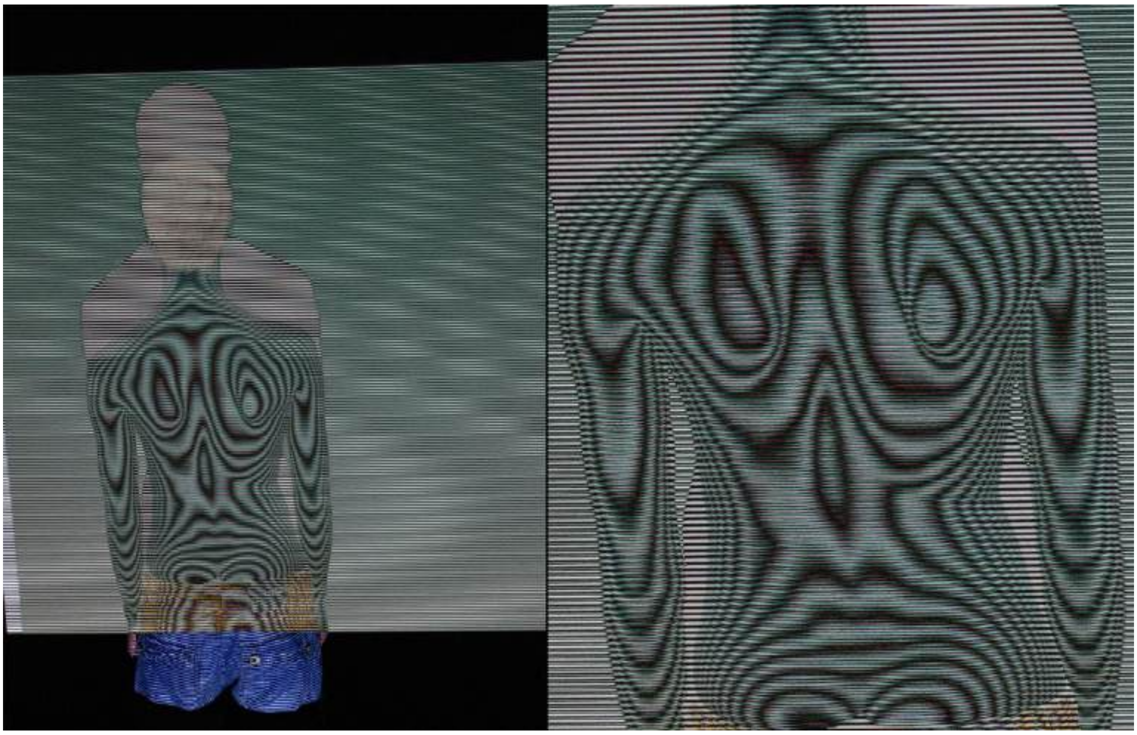


Fig. 25: Original (L) and ROI-cropped (R) moiré image

Function *rgb2gray* is applied in order to convert cropped RGB images into grayscale (Fig. 26). For morphological operations discussed in phase (2), grayscale images contain all the relevant information of moiré stripes. Colour intensity values do not carry additional information here, and their conversion to grayscale does not induce data loss.

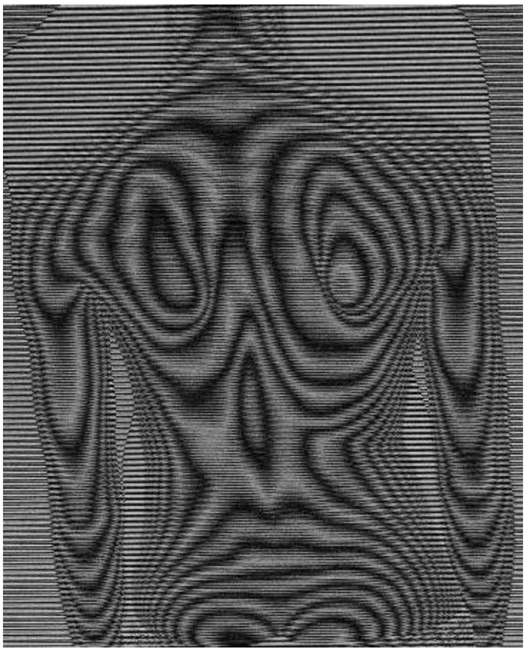


Fig. 26: Grayscale moiré image with ROI

5.1.2 Steps of Moiré Fringe Segmentation

For segmenting MFs, a possible algorithmic approach is introduced. In the segmentation procedure, an empirically established sequence of filtering and morphological operations is used: (1) enhancing contrast, (2) increasing brightness, (3) refining contrast, applying (4) 2-D Gaussian filter and (5) dilation, (6) thresholding and (7) skeletonization.

Table 11: Summary of function parameters applied to moiré image (MI) groups G1 and G2

PHASES	G1 (MI no. 1, 2, 3, 5, 6, 7, 9, 10)	G2 (MI no. 4, 8, 11)
Enhancing contrast [*imadjust by def.*]	3x	3x
Increasing brightness [increase in pixel value]	120	100 for MI no. 4 and 8 110 for MI no. 11
Refining contrast [range of intensity values]	[0.7 1]	[0.7 1]
2-D Gaussian filter [standard deviation]	6	6 for MI no. 4 and 11 8 for MI no. 8
Dilation [structuring element, pixel width, repetition]	square, 3, 3	square, 3, 3
Threshold value	0.41	0.35 for MI no. 4 and 11 0.38 for MI no. 8

5.1.2.1 Enhancing contrast

For mapping the intensity values to new values and thereby enhancing contrast, *imadjust* function was applied in 2 steps. In the first step a slight contrast correction is performed via saturating the bottom 1% and the top 1% of all pixel values three times by the default operation of *imadjust* (Fig. 27).

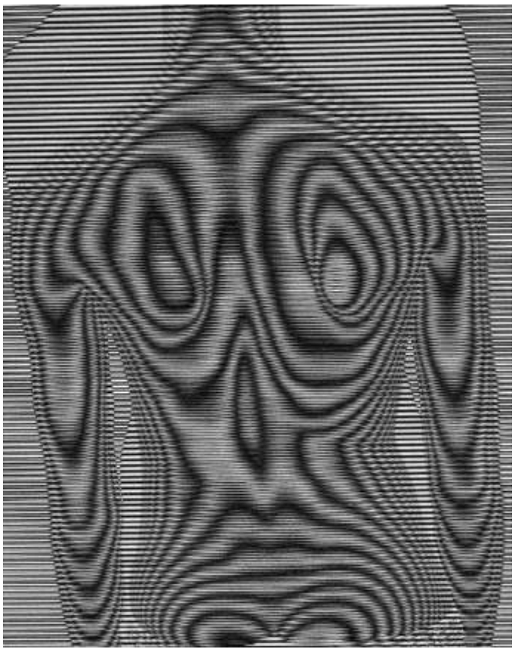


Fig. 27: Result of contrast enhancement applied on grayscale moiré

5.1.2.2 Increasing brightness

Before further contrast enhancement, brightness is increased by increasing pixel values of MIs of G1 by 120 and G2 by 100 and 110, respectively (Fig. 28).

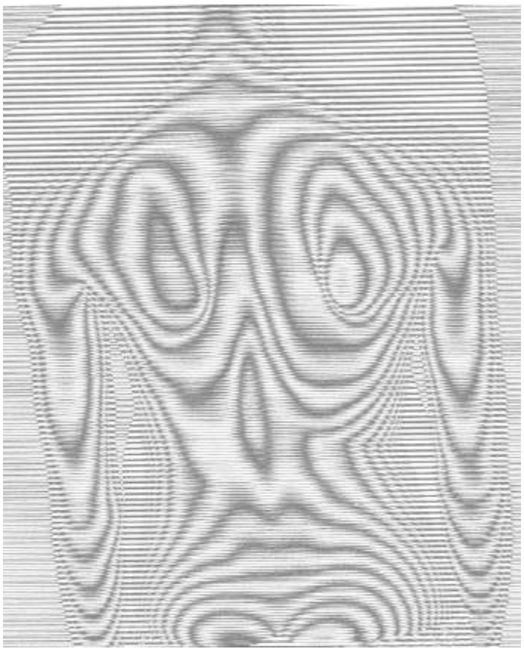


Fig. 28: Result of brightness increase

5.1.2.3 Refining contrast

As the second step in contrast adjustment, intensity values are mapped to new values between 0.7 and 1, by re-applying the function *imadjust*. The result is a stronger contrast of moiré stripes (Fig. 29).

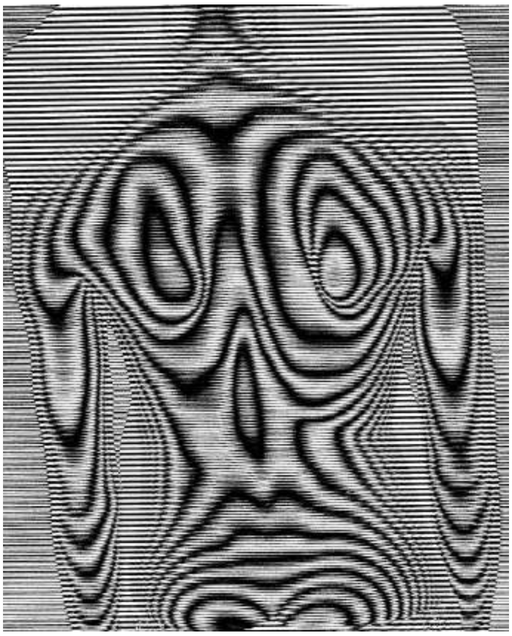


Fig. 29: Result of contrast refinement

5.1.2.4 Applying 2-D Gaussian filter

Image is filtered with a 2-D Gaussian smoothing kernel (*imgaussfilt*) with image specific SD values 6 or 8 (Fig. 30).

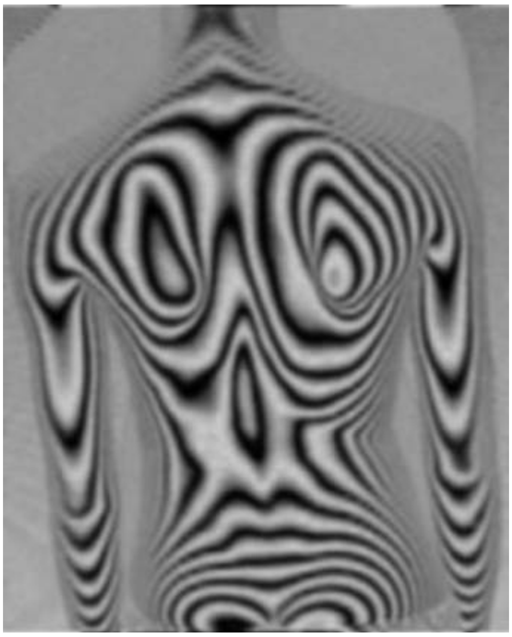


Fig. 30: Result of 2-D Gaussian filtering

5.1.2.5 Applying dilation

Blurred grayscale image is dilated by using *imdilate* and morphological structuring element *strel*. Dilation is applied three times in combination of square structuring element with a width of 3 pixels. In Fig. 31, resulting differences from the previous step (2-D Gaussian filter) may not be obvious, however, dilation supports the results of thresholding and skeletonizing operations by gradually enlarging the boundaries of regions of foreground pixels.

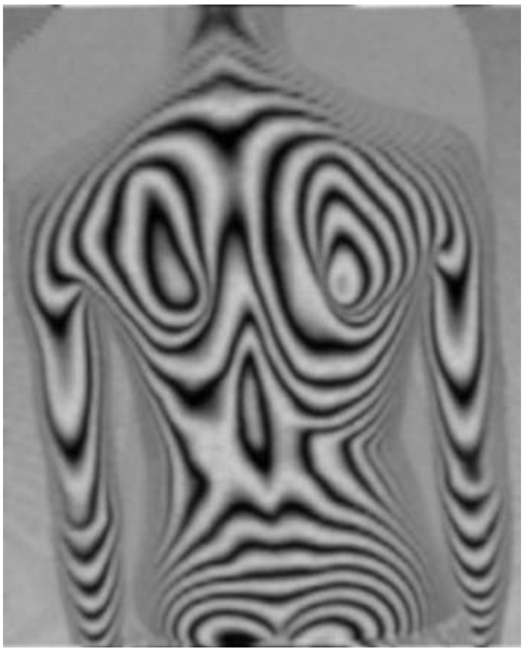


Fig. 31: Result of dilation

5.1.2.6 Applying thresholding

Function *imbinarize* is used to convert the image to a binary image, based on a threshold value: all pixel values above a globally determined threshold are replaced with ones and all other values with zeros. The threshold value applied is covered in the range between 0.35 and 0.41 (Fig. 32).

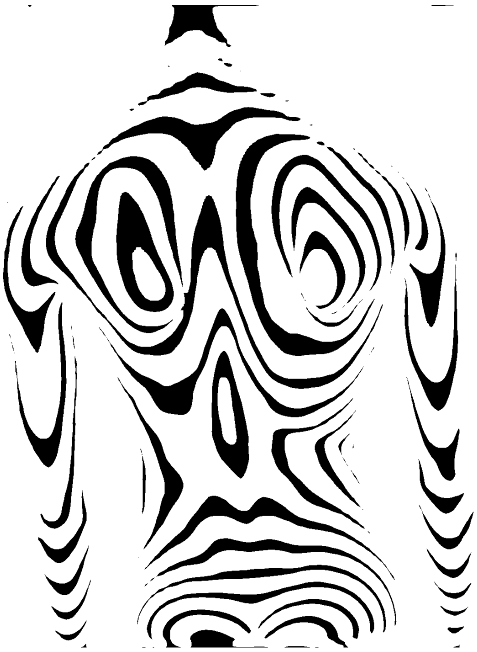


Fig. 32: Result of thresholding

5.1.2.7 Applying skeletonization

Skeletonization was performed by using *bwmorph* function for morphological operations, specified as 'thin'. The operation 'thin' is applied for thinning binarized images to single lines, and repeated until the image no longer changes (i.e. parameter 'Inf' in the function input). The inputs of *bwmorph* are provided by complements of binarized images generated with the function *imcomplement*. For a better visualization of the results, lines of skeletonized images are fattened by applying the operation 'fatten' once. The result is shown enlarged as re-complemented image (Fig. 33) and as overlay on binarized (Fig. 34) and colour ROI images (Fig. 35).

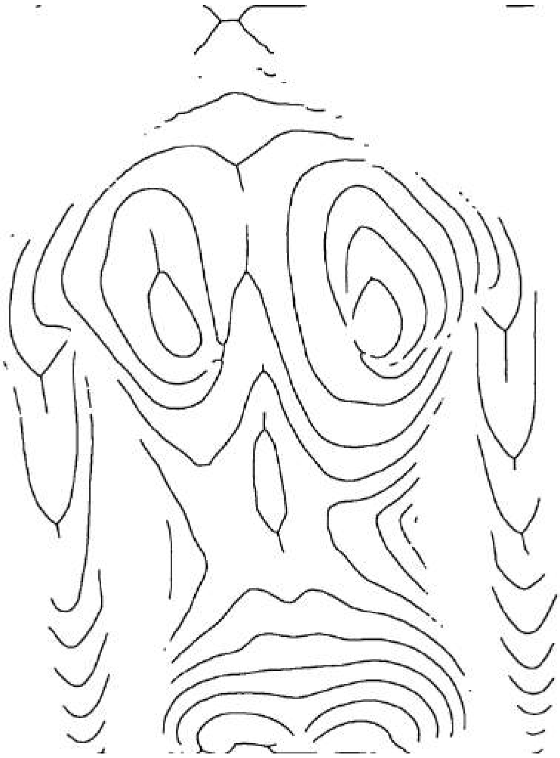


Fig. 33: Result of skeletonization: segmented moiré fringes

Fig. 34: Overlay of segmented moiré fringes (orange) on thresholded image (black)

Fig. 35: Overlay of segmented moiré fringes (orange) on colour ROI

5.2 Moiré Fringe Segmentation by Adaptive Function Parameters

In the second phase of the research on MF segmentation, a fully automated segmenting algorithm has also been developed. Adaptive function parameters were applied on the same MIs and under the same condition as presented in sec 6.1.

5.2.1 Steps of Adaptive Moiré Fringe Segmentation

In the segmenting procedure, the previously introduced, empirically established sequence of filtering and morphological operations are modified and completed by (1) enhancing contrast based on root mean square (RMS) values, (2) applying 2D-Gaussian filter based on RMS values, (3) applying histogram equalization, (4) applying 2D-Gaussian filter based on peak signal-to-noise ratio (PSNR), (5) calculating global image threshold using Otsu's method and (6) applying skeletonization.

5.2.1.1 Enhancing contrast based on RMS values

Contrast enhancement applied is similar to the static solution of research phase 1 (see sec. 5.1) where the intensity values in the original’s grayscale are mapped to new values between 0 and 1. In the adaptive method, the only difference is the upper limit of the intensity value that is calculated by 1 minus the RMS levels computed along the first array dimension (rows) of the image. Since MIs are N-by-M matrices with N > 1, the calculated RMSs represent 1-by-M row vectors containing the RMS levels of the columns of the images. Contrast enhancement is performed on MIs by using the *imadjust* function for each column based on their RMS levels (Fig. 36).

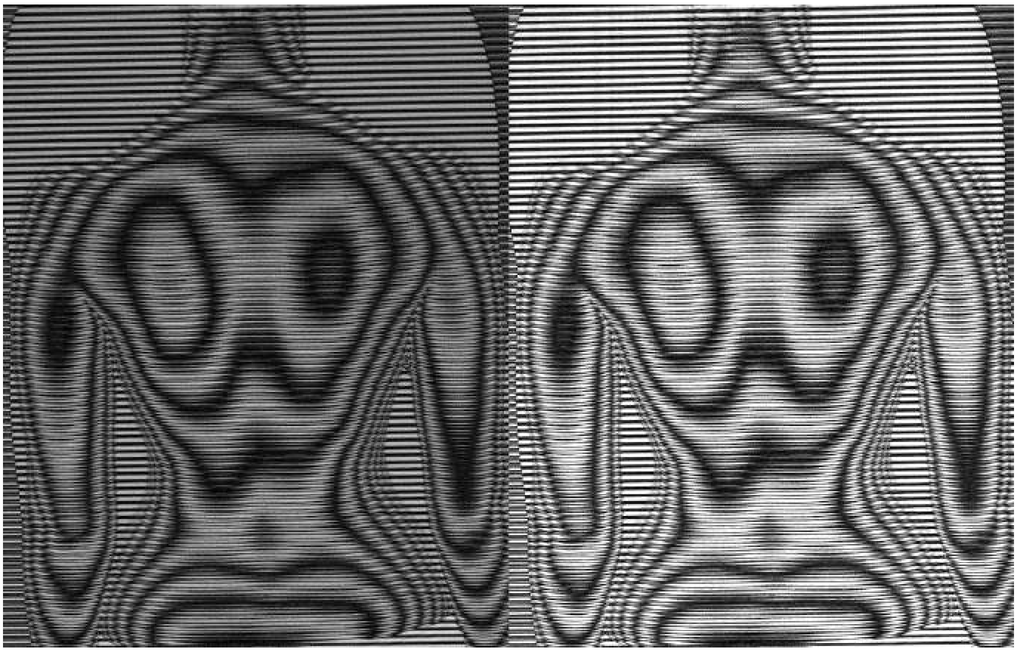


Fig. 36: Result of adaptive contrast enhancement (R) applied on original's grayscale (L)

5.2.1.2 Applying 2-D Gaussian filter based on RMS values

Contrast enhanced image is filtered by 2-D Gaussian padding (*imgaussfilt*) with an experimental number of 10×RMS value calculated from RMS levels of image columns of pixels $g(x, y-4)$ and $g(x, y+4)$ horizontally, and $g(x-4, y)$ and $g(x+4, y)$ vertically. The smoothing kernel is applied in a loop on the image with a step size of 4. Pixels to be processed are defined by a maximum horizontal and vertical four-pixel distance from the current pixel of the loop. In the adaptive 2-D Gaussian filter, the RMS value, the step size and the maximum horizontal and vertical distance from the current pixel of the loop are all experimental numbers that proved to be suitable in the research for an adaptive solution. The result of the 2D-Gaussian filter based on RMS values is shown in Fig.37.

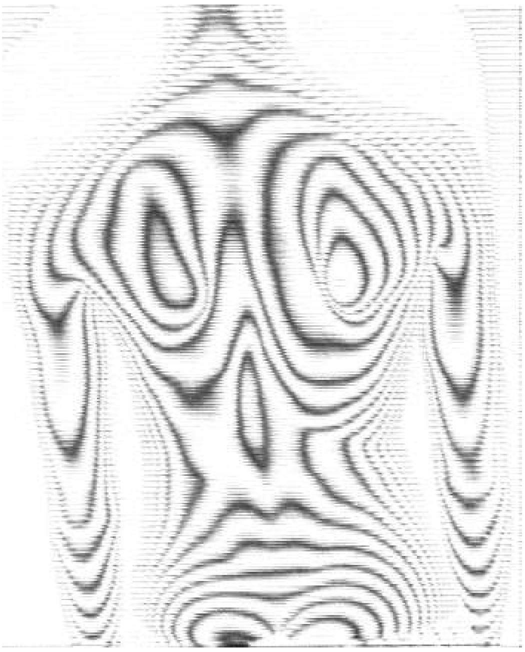


Fig. 37: Result of 2-D Gaussian filtering based on root mean square values

5.2.1.3 Applying histogram equalization

Contrast enhancement is applied by using histogram equalization function (*histeq)* that outputs an approximately flat image with 64 bins by default. As a result of this, a significant contrast enhancement and a still acceptable increase in image noise—mainly caused by residual grating—can be observed on 2-D Gaussian-padded images (Fig. 38).

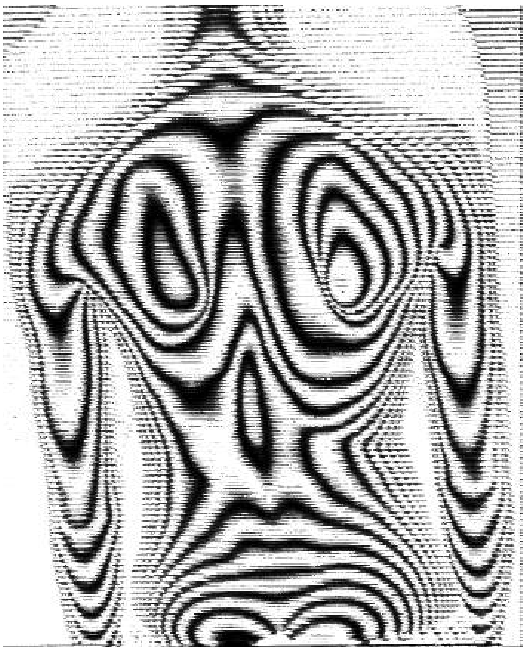


Fig. 38: Contrast enhancement by histogram equalization

5.2.1.4 Applying 2-D Gaussian filter based on PSNR

For reducing image noise amplified by histogram equalization, an additional 2-D Gaussian filter (*imgaussfilt*) is applied with PSNR-based SD values (Fig. 39). Standard deviation value is defined experimentally by calculating the absolute value of the peak signal-to-noise ratio for the histogram equalized image, with the original's grayscale image as the reference.

Fig. 39: 2-D Gaussian filtered image based on PSNR

5.2.1.5 Calculating global image threshold using Otsu's method

For automatic image thresholding, function *imbinarize* is used with value ‘global’ to convert the image to a binary image by calculating global image threshold using Otsu’s method [157] (Fig. 40).

Fig. 40: The result of automatic image thresholding by using Otsu's method

5.2.1.6 Applying skeletonization

The process of skeletonization follows the same concept introduced in sec. 5.1.2.7. Fig. 41 shows the skeletonized image—the result of the adaptive fringe segmentation. The result is shown enlarged and as overlay on binarized (Fig. 42) and colour ROI images (Fig. 43).

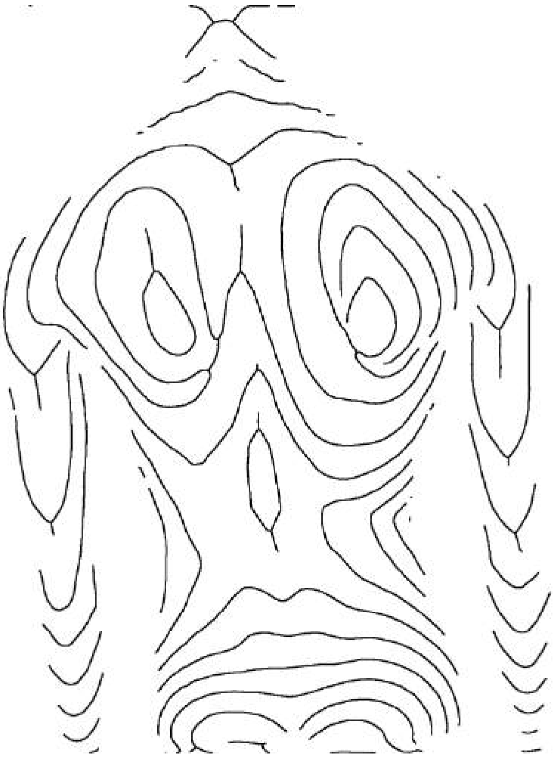


Fig. 41: Skeletonized image of adaptive fringe segmentation

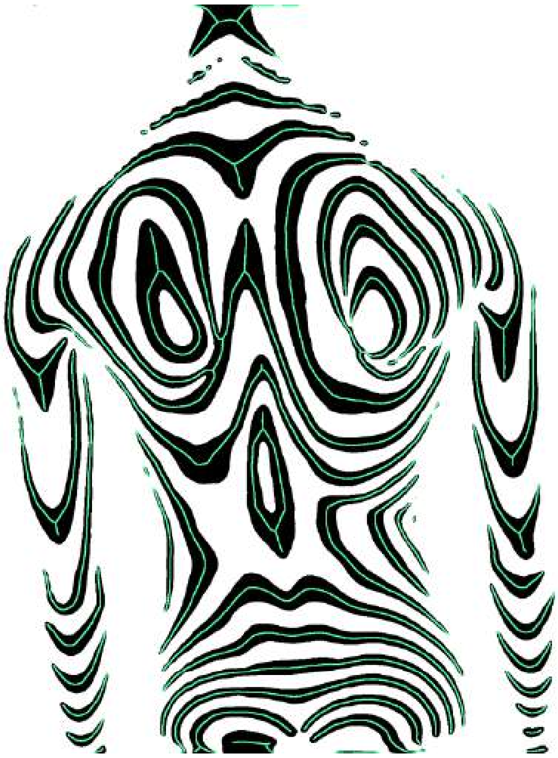


Fig. 42: Overlay of adaptive segmented moiré fringes (green) on thresholded image (black)

Fig. 43: Overlay of adaptive segmented moiré fringes on colour ROI

5.3 Results and discussion

Results show that the static segmenting method is simple, fast to process and, for the most part of the image, follows the moiré stripes accurately. The adaptive algorithm provides a similar segmentation with a significantly slower performance caused by the process of the RMS-based 2-D Gaussian filter. Figs. 44-65 show the static and adaptive segmented MFs side-by-side on the grayscale and superimposed on the original image. The average elapsed time from grayscale conversion to skeletonization per image is 0.485s for the static, and 390.921s for the adaptive algorithm. In Table 12 and 13, the time courses of the static and adaptive algorithms, with exclusion of manual ROI selection, are summarized in average elapsed and processing time. A summary of the steps of both algorithms is given in Table 14.

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. 66). For removing unwanted branches and specifying the minimum branch length of the segmented skeleton, *bwskel* function with operation 'MinBranchLength' seems to be an adequate solution.

In terms of general usability, despite the fast execution speed of the static algorithm, the necessity of 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 empirically determined and implemented in the code. Therefore, static function parameters are desired to be eliminated by automatic adaptive and dynamic parameterization. This elimination was 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 RMS values remains to be optimized.

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 [148].

The full codes for static and adaptive algorithms are given in Appendix E and F.

Table 12: Time course of the segmenting algorithm with static parameters

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 13: Time course of the segmenting algorithm with adaptive parameters

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 14: 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	—

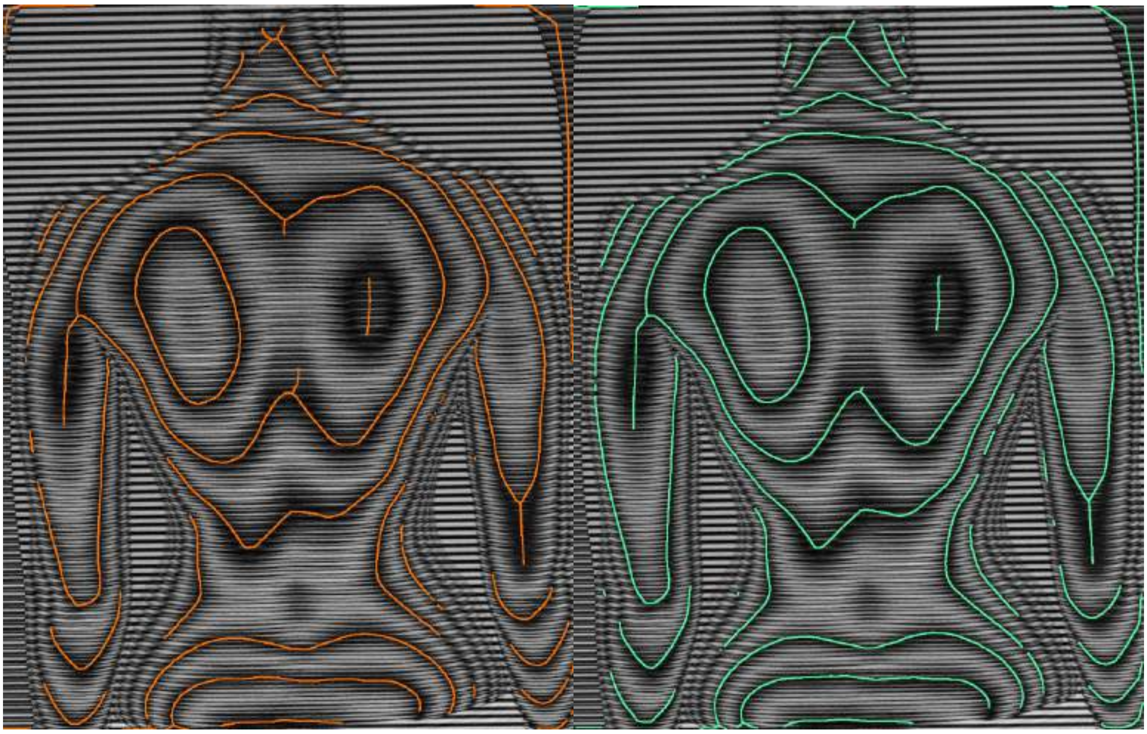


Fig. 44: Static (L) and adaptive (R) segmented moiré fringes of image no. 1.

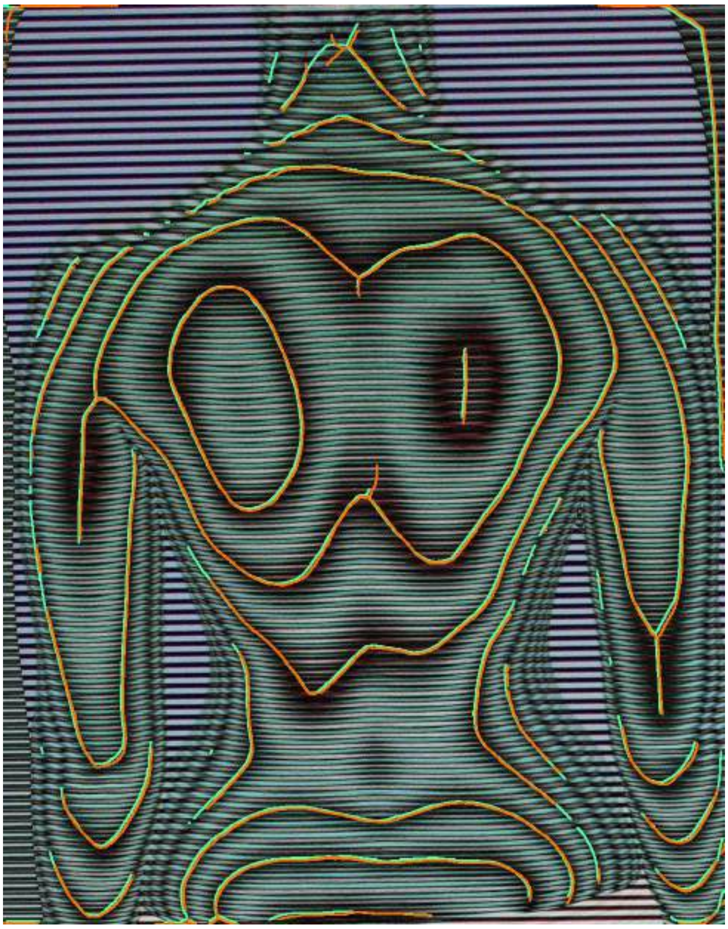


Fig. 45: Static (orange) and adaptive (green) segmented moiré fringes on image no. 1.

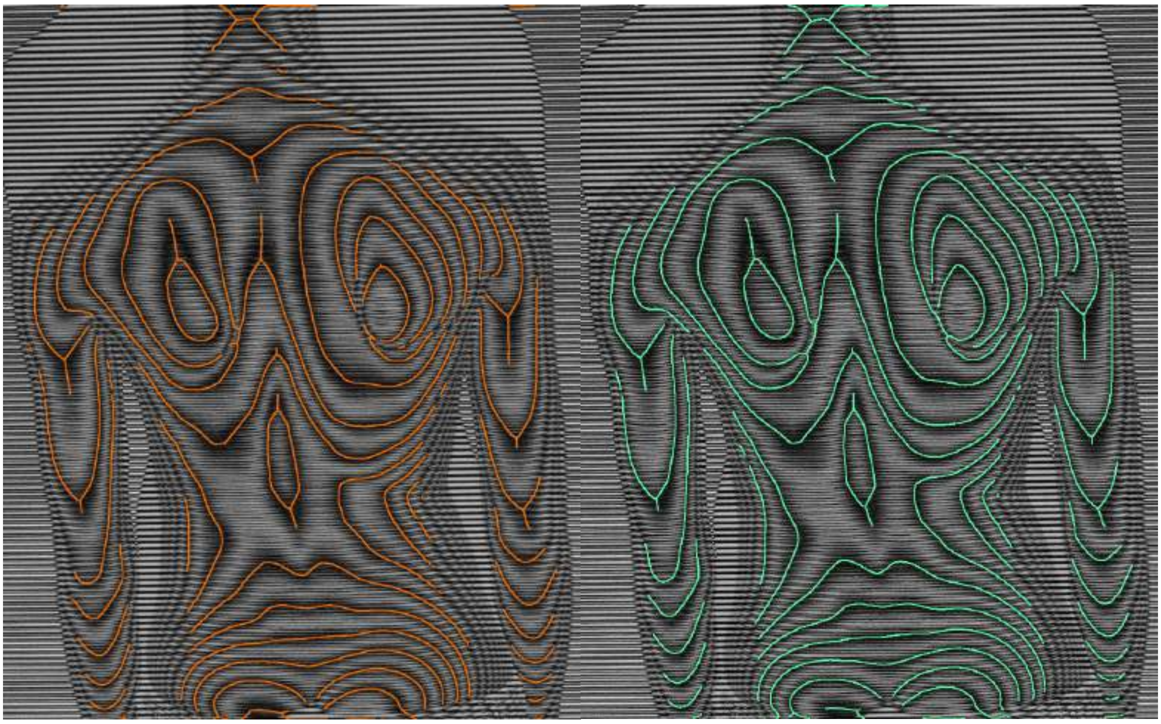


Fig. 46: Static (L) and adaptive (R) segmented moiré fringes of image no. 2.

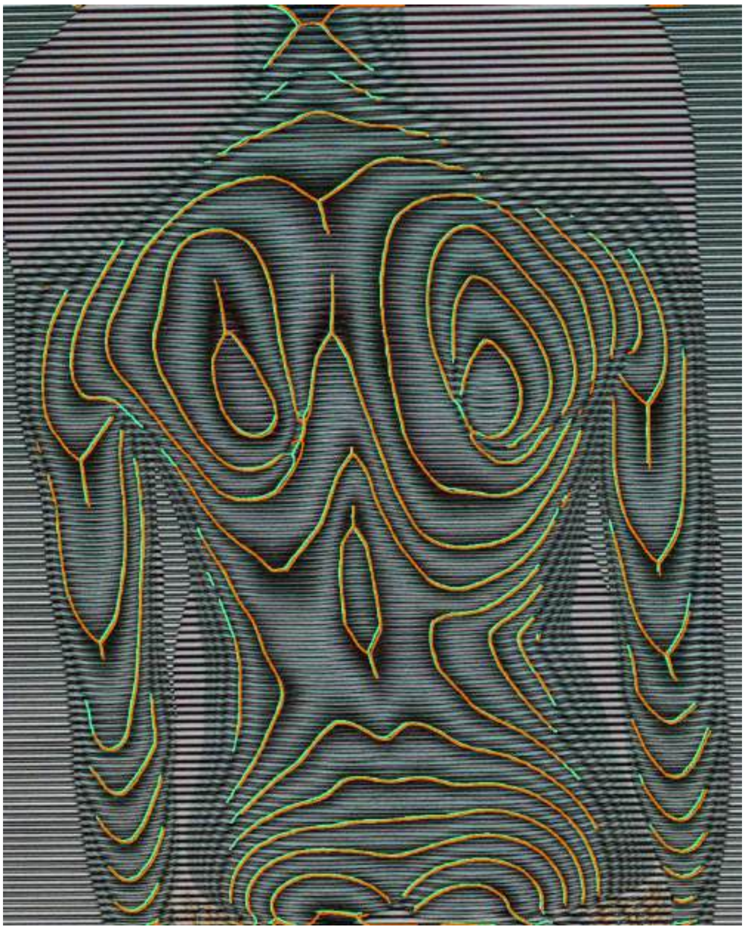


Fig. 47: Static (orange) and adaptive (green) segmented moiré fringes on image no. 2.

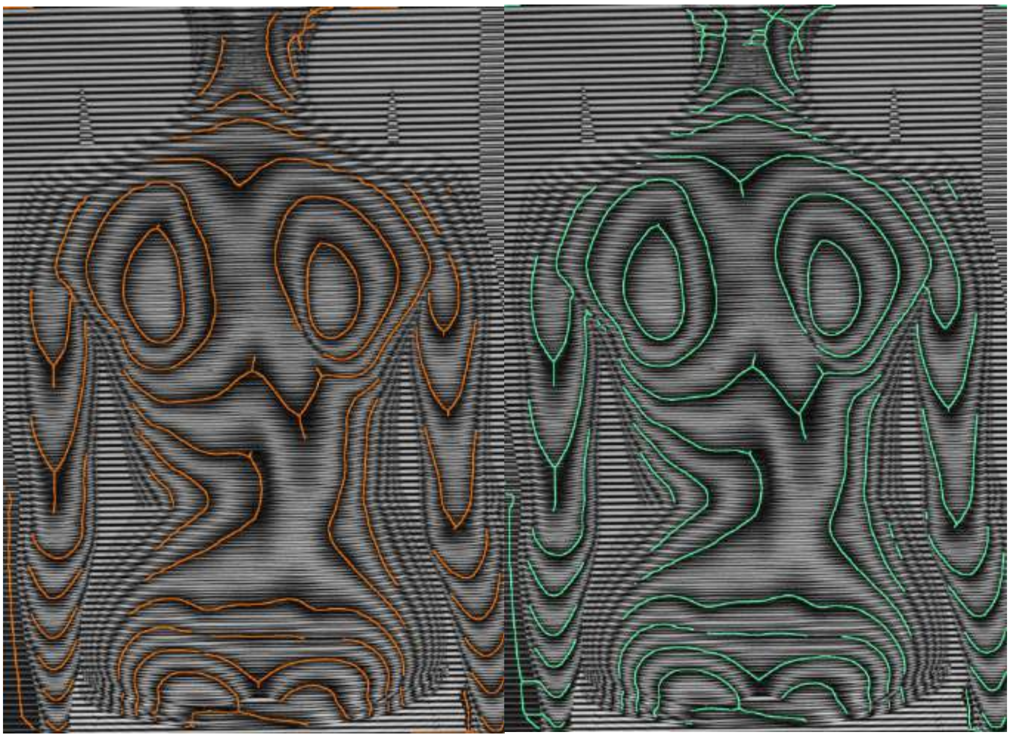


Fig. 48: Static (L) and adaptive (R) segmented moiré fringes of image no. 3.

Fig. 49: Static (orange) and adaptive (green) segmented moiré fringes on image no. 3.

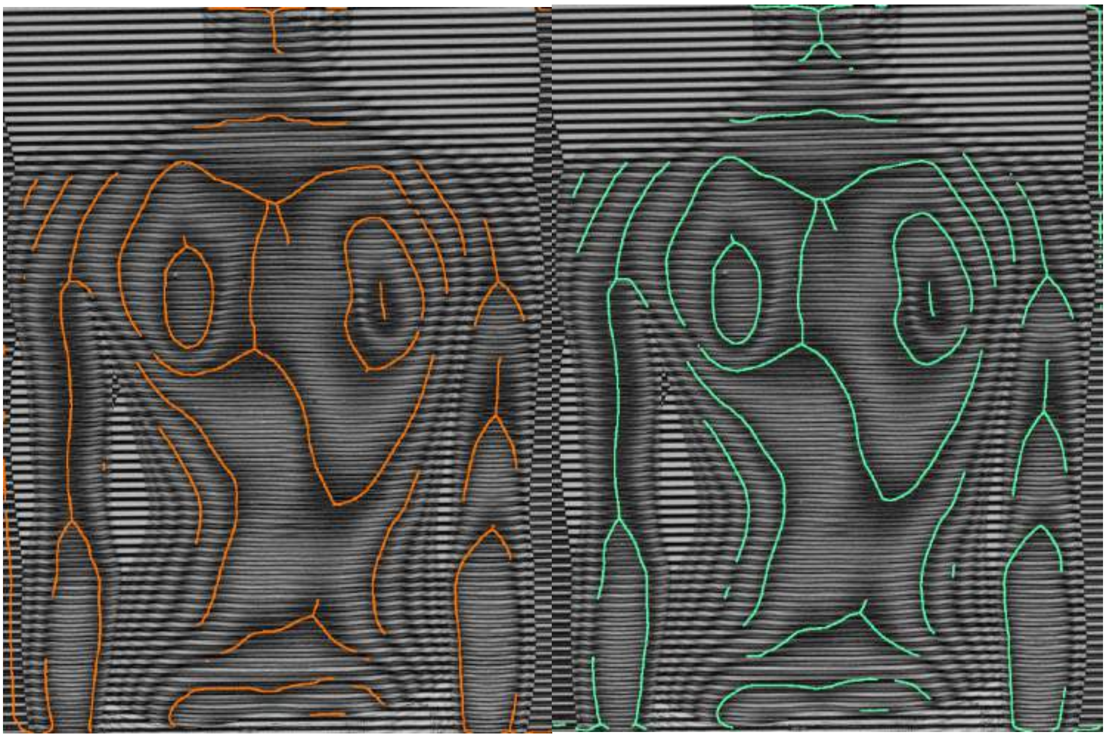


Fig. 50: Static (L) and adaptive (R) segmented moiré fringes of image no. 4.

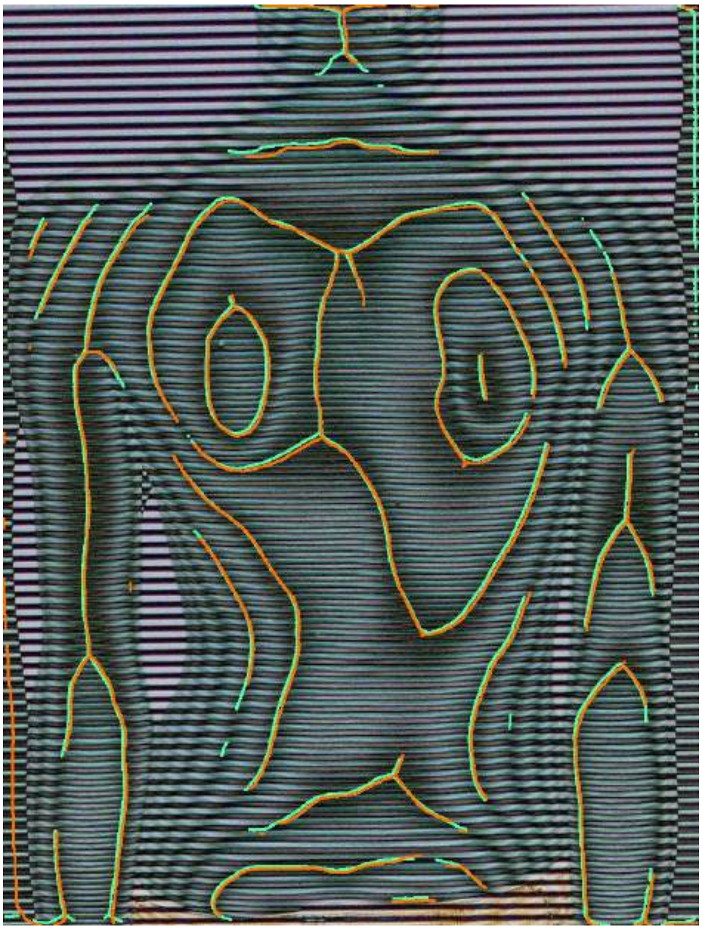


Fig. 51: Static (orange) and adaptive (green) segmented moiré fringes on image no. 4

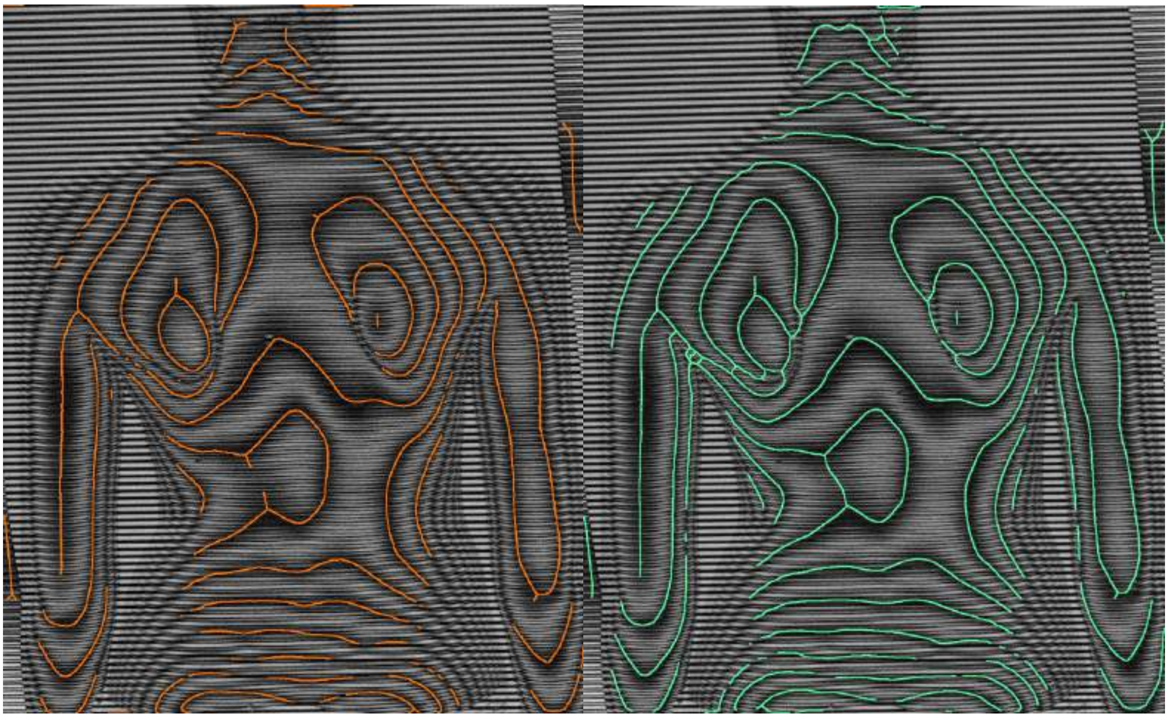


Fig. 52: Static (L) and adaptive (R) segmented moiré fringes of image no. 5.

Fig. 53: Static (orange) and adaptive (green) segmented moiré fringes on image no. 5.

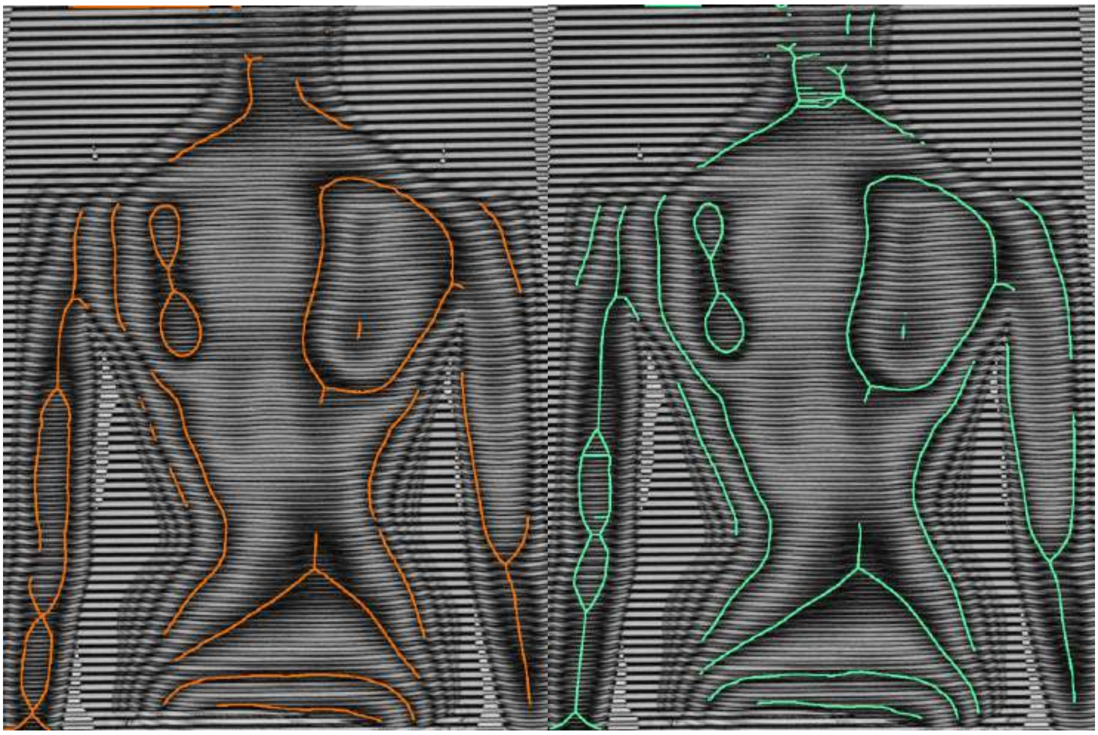


Fig. 54: Static (L) and adaptive (R) segmented moiré fringes of image no. 6.

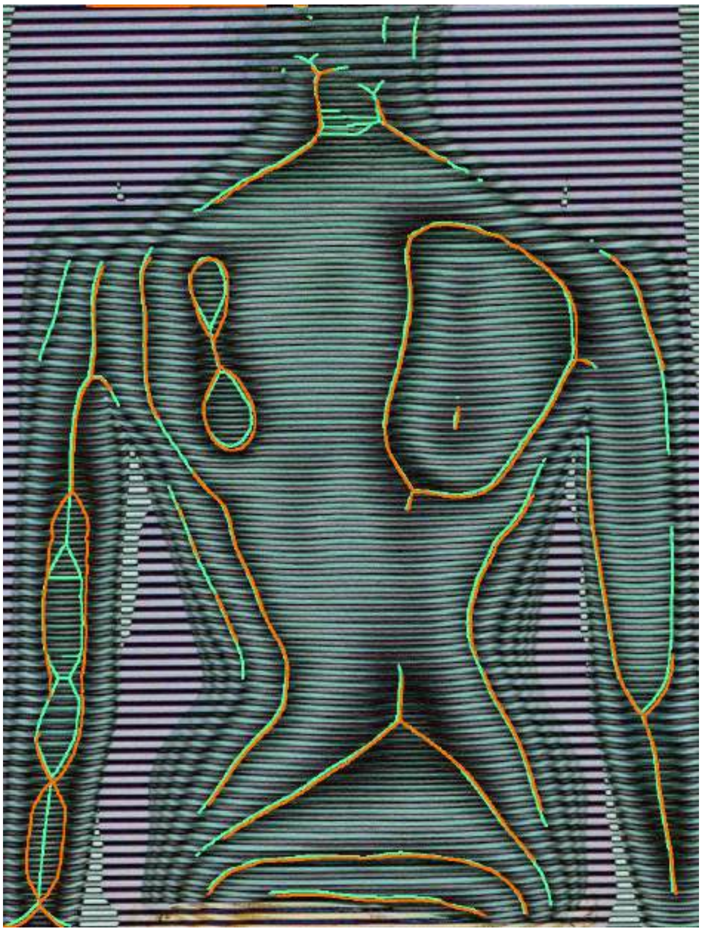


Fig. 55: Static (orange) and adaptive (green) segmented moiré fringes on image no. 6.

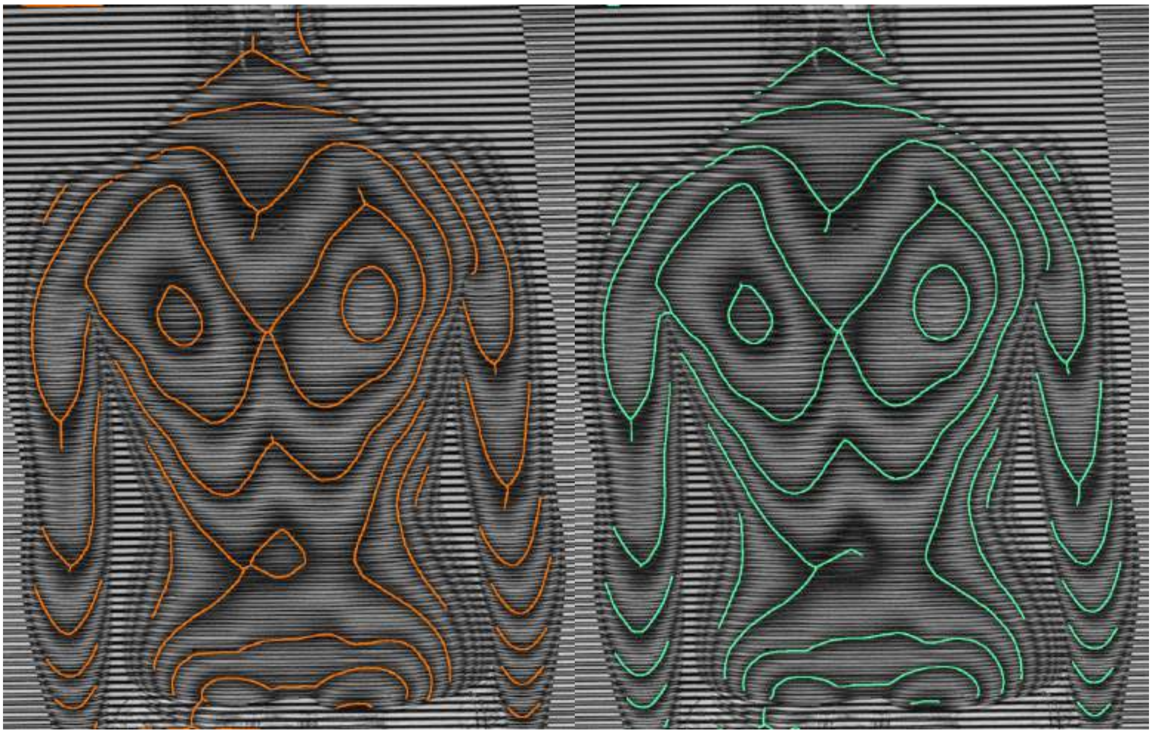


Fig. 56: Static (L) and adaptive (R) segmented moiré fringes of image no. 7.

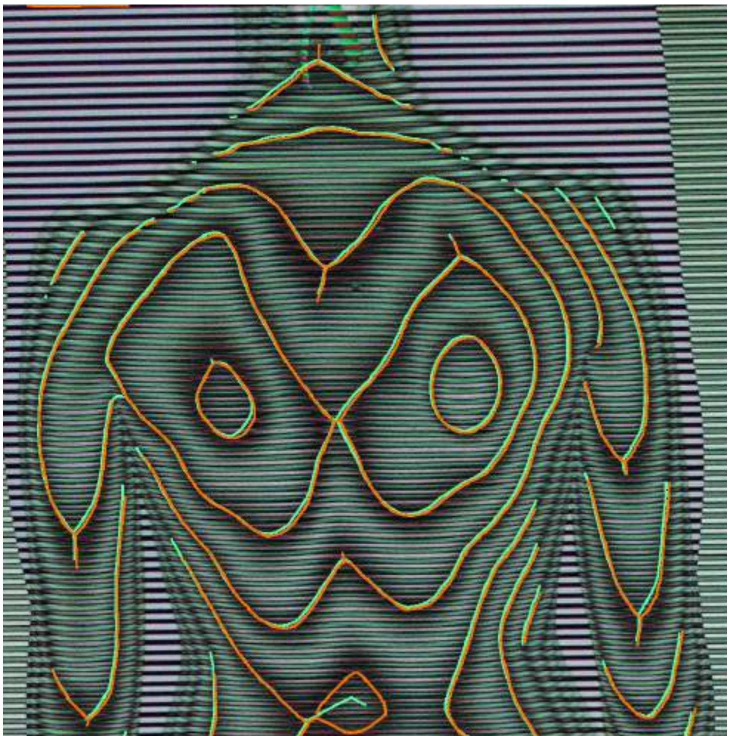


Fig. 57: Static (orange) and adaptive (green) segmented moiré fringes on image no. 7.

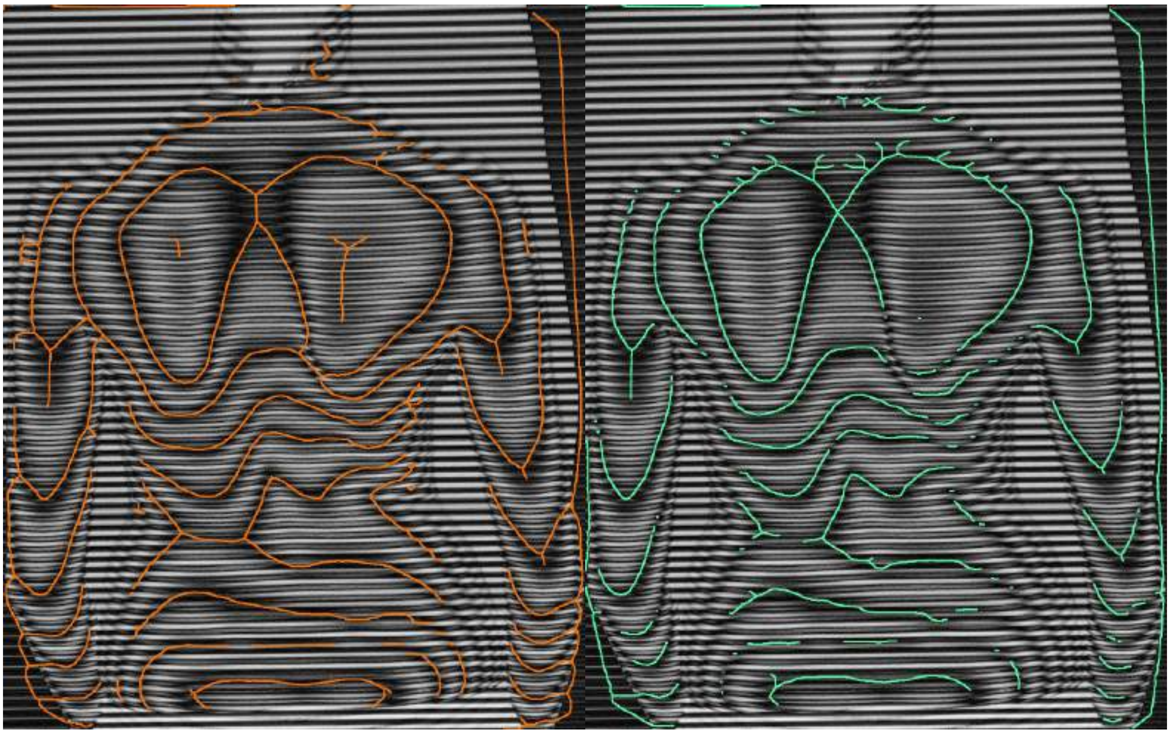


Fig. 58: Static (L) and adaptive (R) segmented moiré fringes of image no. 8.

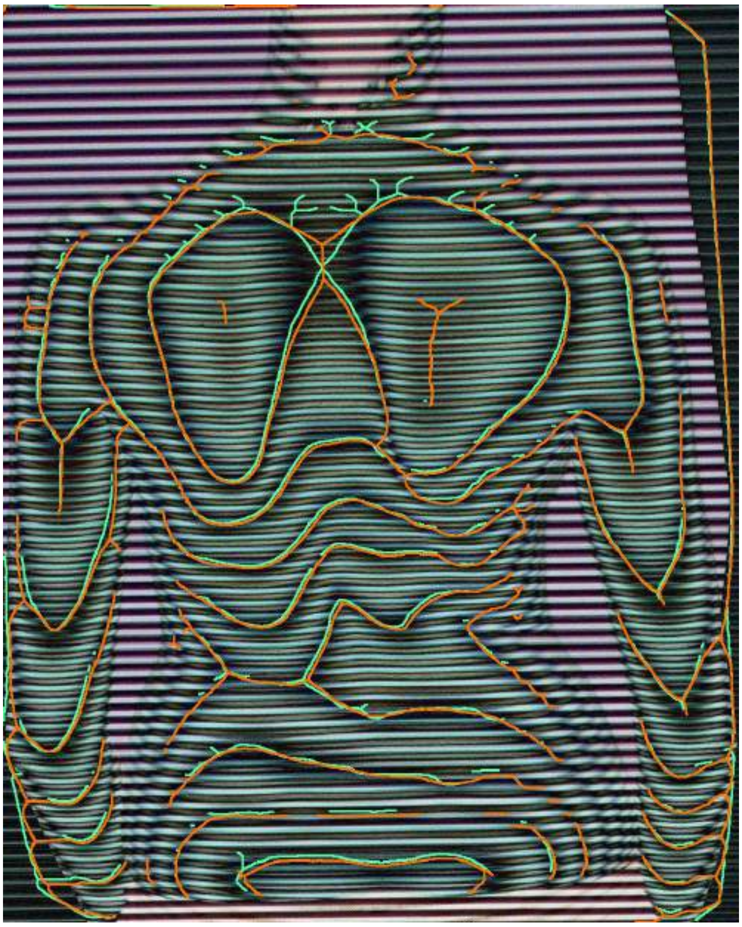


Fig. 59: Static (orange) and adaptive (green) segmented moiré fringes on image no. 8.

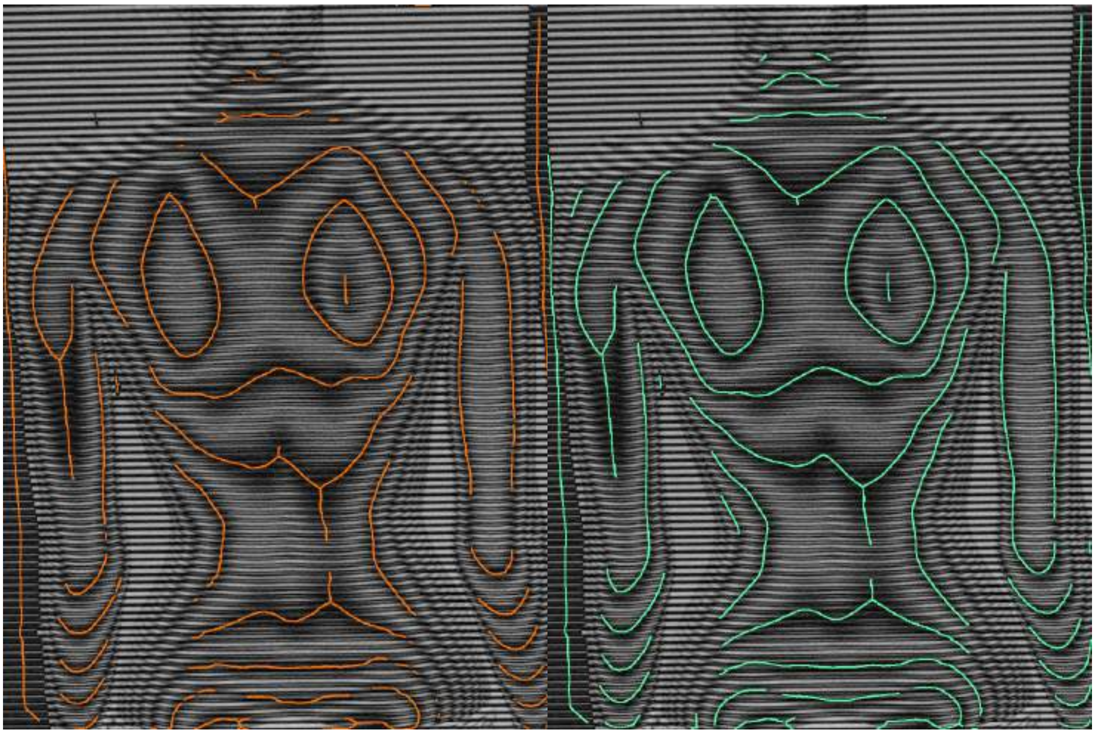


Fig. 60: Static (L) and adaptive (R) segmented moiré fringes of image no. 9.

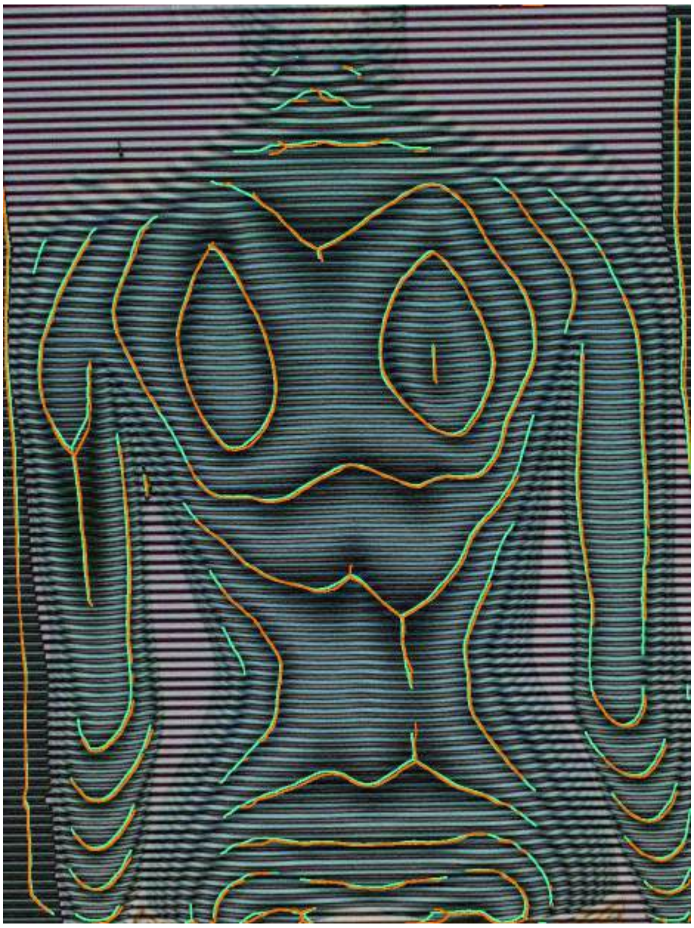


Fig. 61: Static (orange) and adaptive (green) segmented moiré fringes on image no. 9.

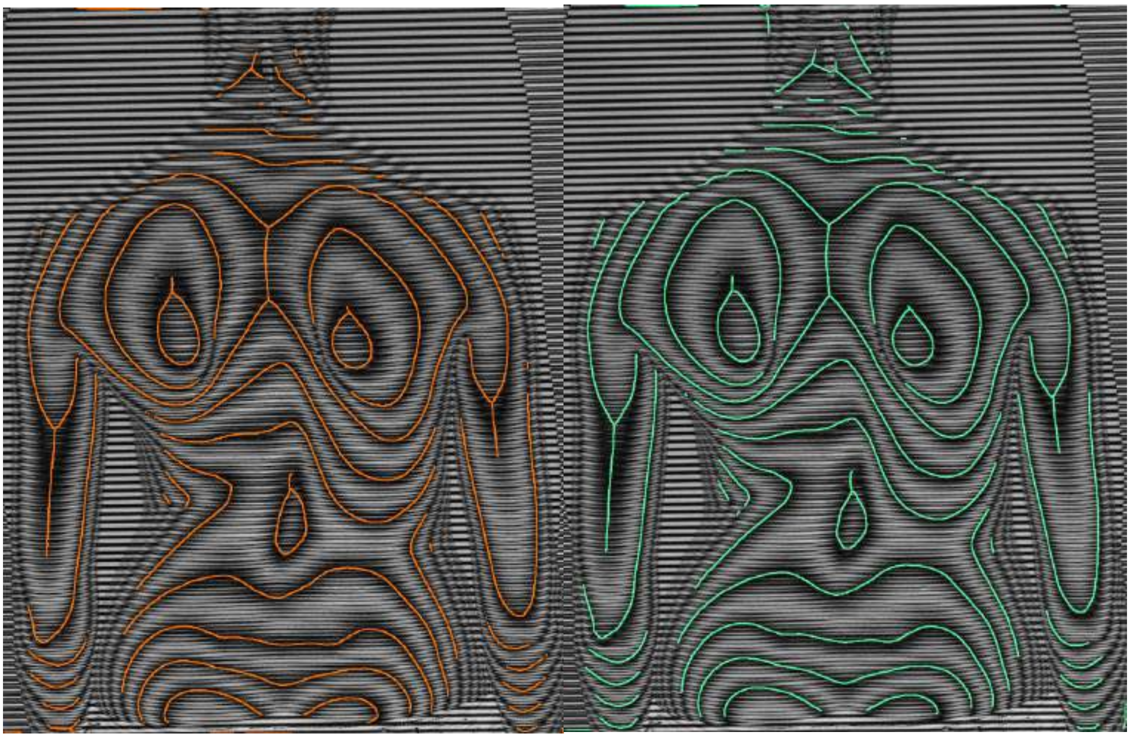


Fig. 62: Static (L) and adaptive (R) segmented moiré fringes of image no. 10.

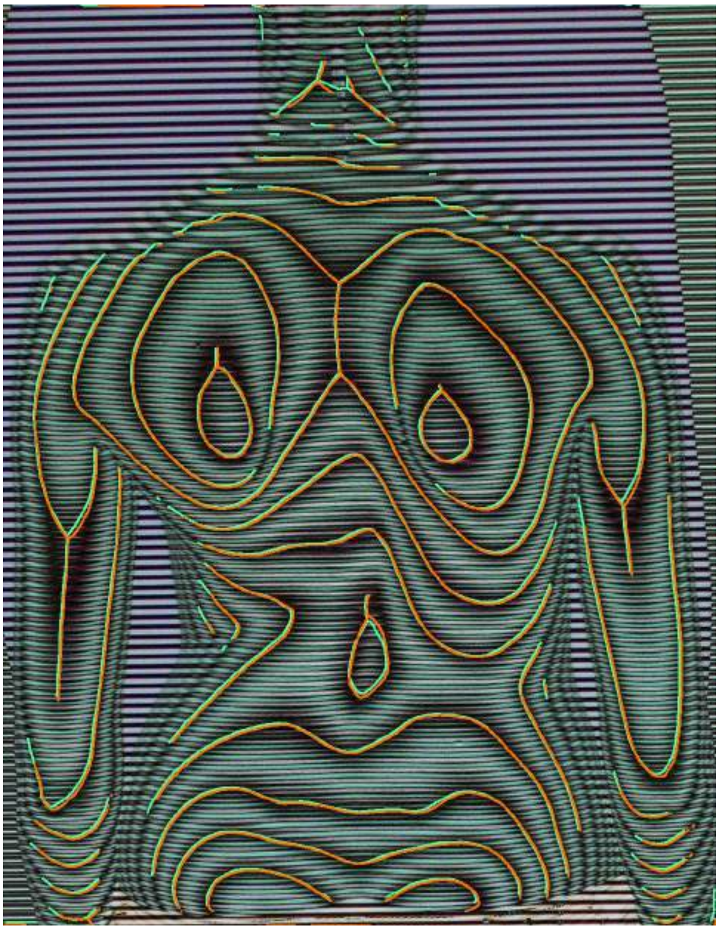


Fig. 63: Static (orange) and adaptive (green) segmented moiré fringes on image no. 10.

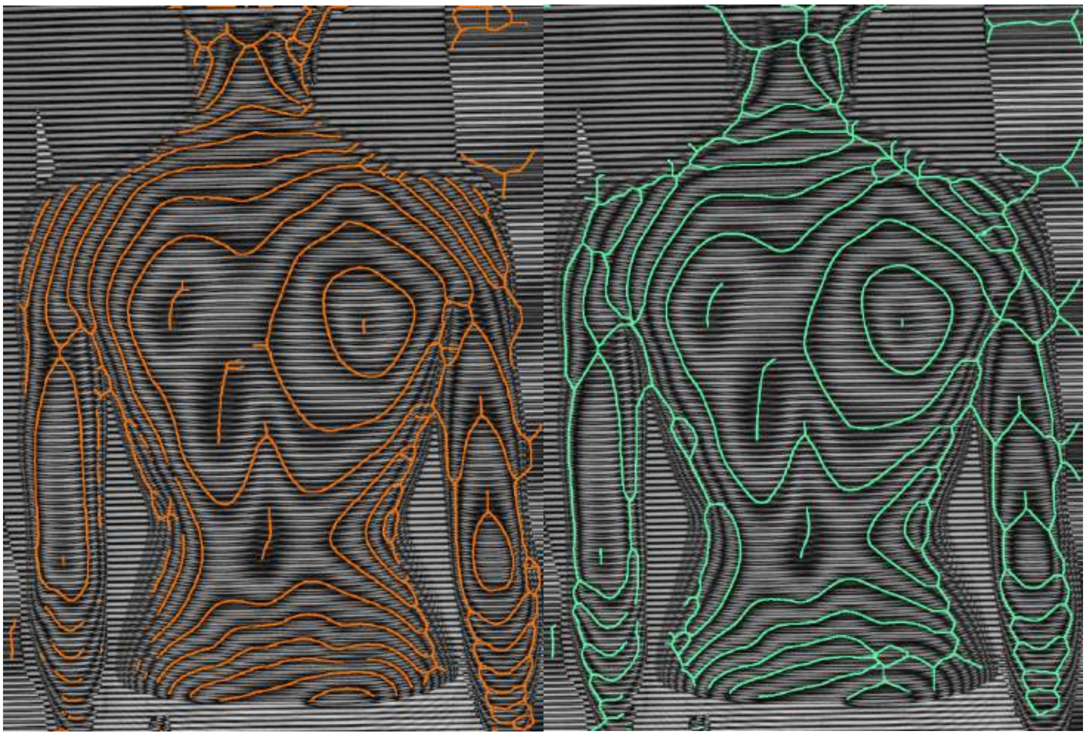


Fig. 64: Static (L) and adaptive (R) segmented moiré fringes of image no. 11.

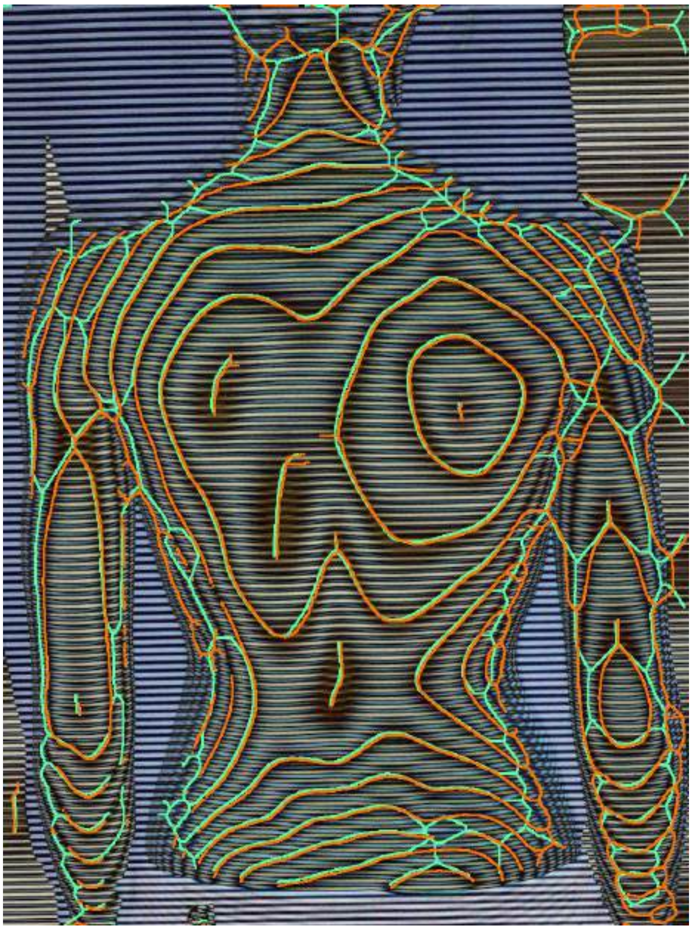


Fig. 65: Static (orange) and adaptive (green) segmented moiré fringes on image no. 10.

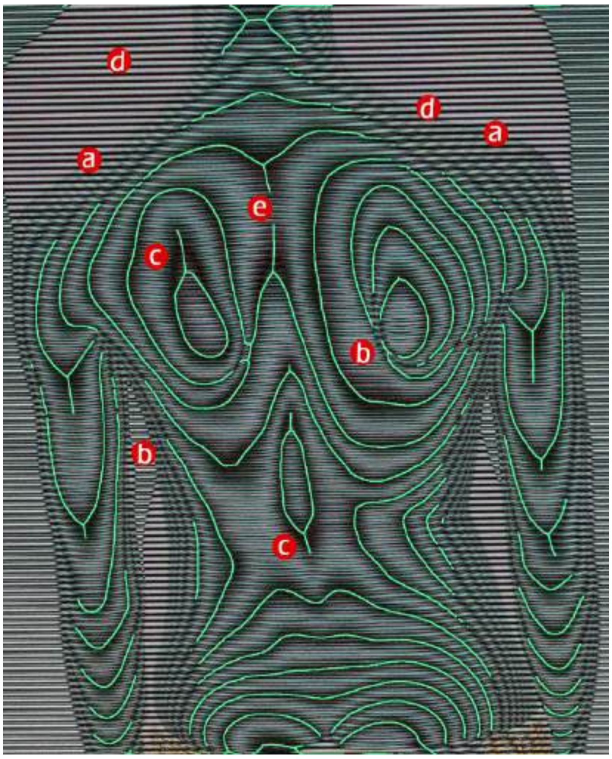


Fig. 66: Problems to be handled in moiré fringe segmenting algorithms
(Illustrated on static segmented MI no. 2)

(a-c) pale, convergent, and wider/blurred moiré fringes
(d) noise of residual grating
(e) unwanted branches

5.4 Conclusion

In sec. 5.1, the initial phase of research on MF segmentation of scoliotic spines is introduced, presenting an algorithmic sequence of filtering and morphological operations with static function parameters in MATLAB environment. 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.

In sec. 5.2, based on the static algorithm, a fully automated adaptive segmenting solution was introduced. 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. The adaptive algorithm, although it eliminates the need for manual re-adjustment of function parameters, its execution speed at applying 2-D Gaussian filter based on RMS values remains to be optimized.

In light of their results, by further R&D, both algorithmic solutions are suitable to replace time demanding and complex segmentation methods.

6 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, after producing a base grid on the patient's back by using PMT, (see step 4 in sec. 3.2.1), 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 (sec. 5.1) and adaptive (sec. 5.2) 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 (sec. 4.1.5). In a later stage of the MITS project, a SOAR analysis is planned to be conducted for evaluating the product and its innovation potential with 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 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, which—as an additional benefit—also serves the purposes of health awareness and scientific communication.

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.

Finally, I hope I will soon be able to report on the MITS project, which includes both realized software and hardware. However, these would only offer frames for further 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.

I hope to wish you a good job with my fully implemented software soon!

Acknowledgement

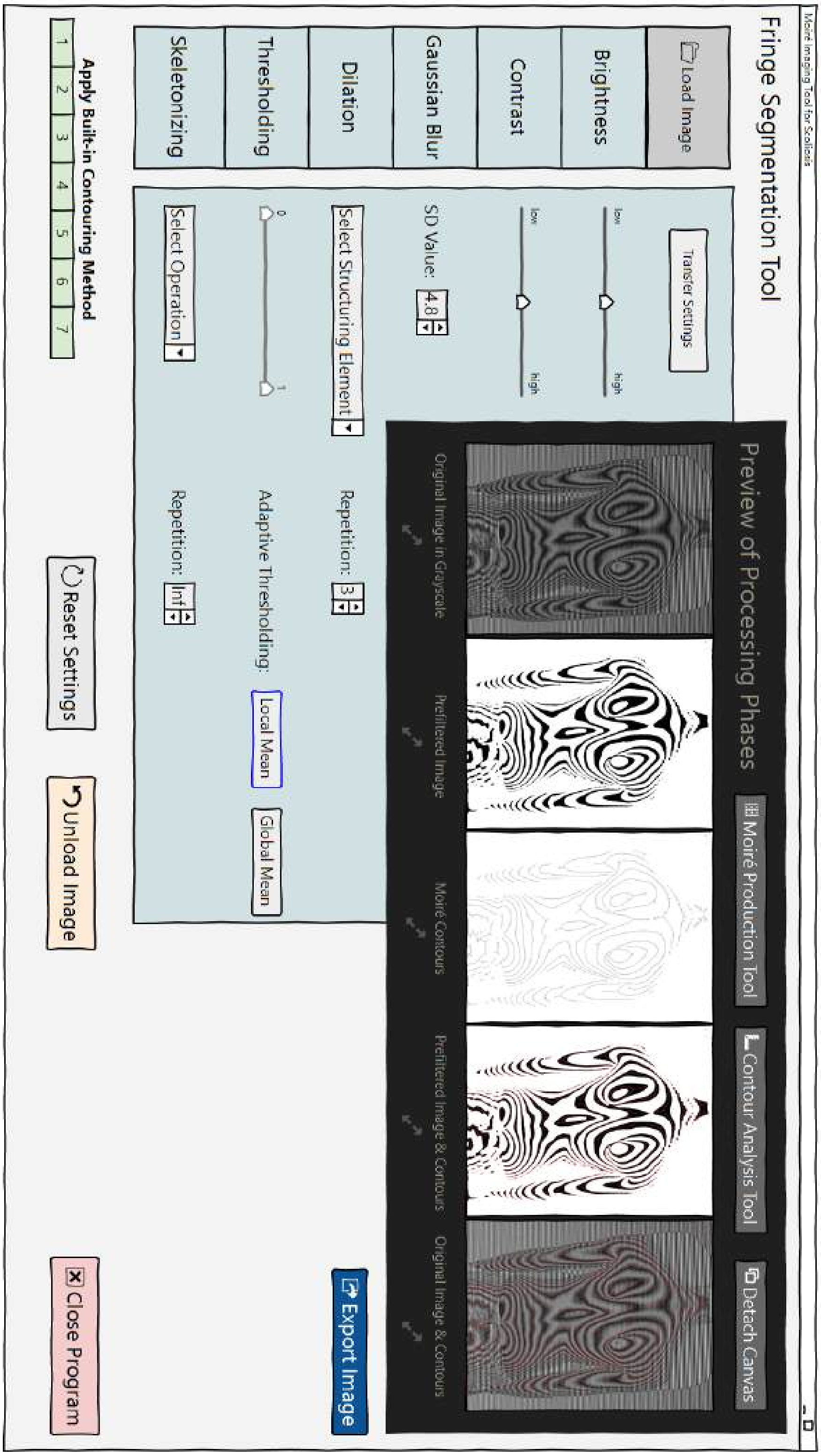
Thank you for accepting and supporting me—in chronological order:

My parents
Dr. Evelin Gabriella Hargitai
My dear friends Géza Faragó and Sándor Bíró
Dr. Ákos Antal
Dr. Sándor Nagy
Dr. Lajos Bogár
Dr. Péter Than
Dr. Miklós Tunyogi-Csapó
István Joó
Ferenc Marlok
Katalin Prommer
Dr. Wolfgang Birkfellner
Dr. Andor Dániel Magony

Appendices

Appendix A: Concept Preview of Moiré Segmentation Tool

Screenshot captured in WireframeSketcher (14-day trial of v6.2.3)



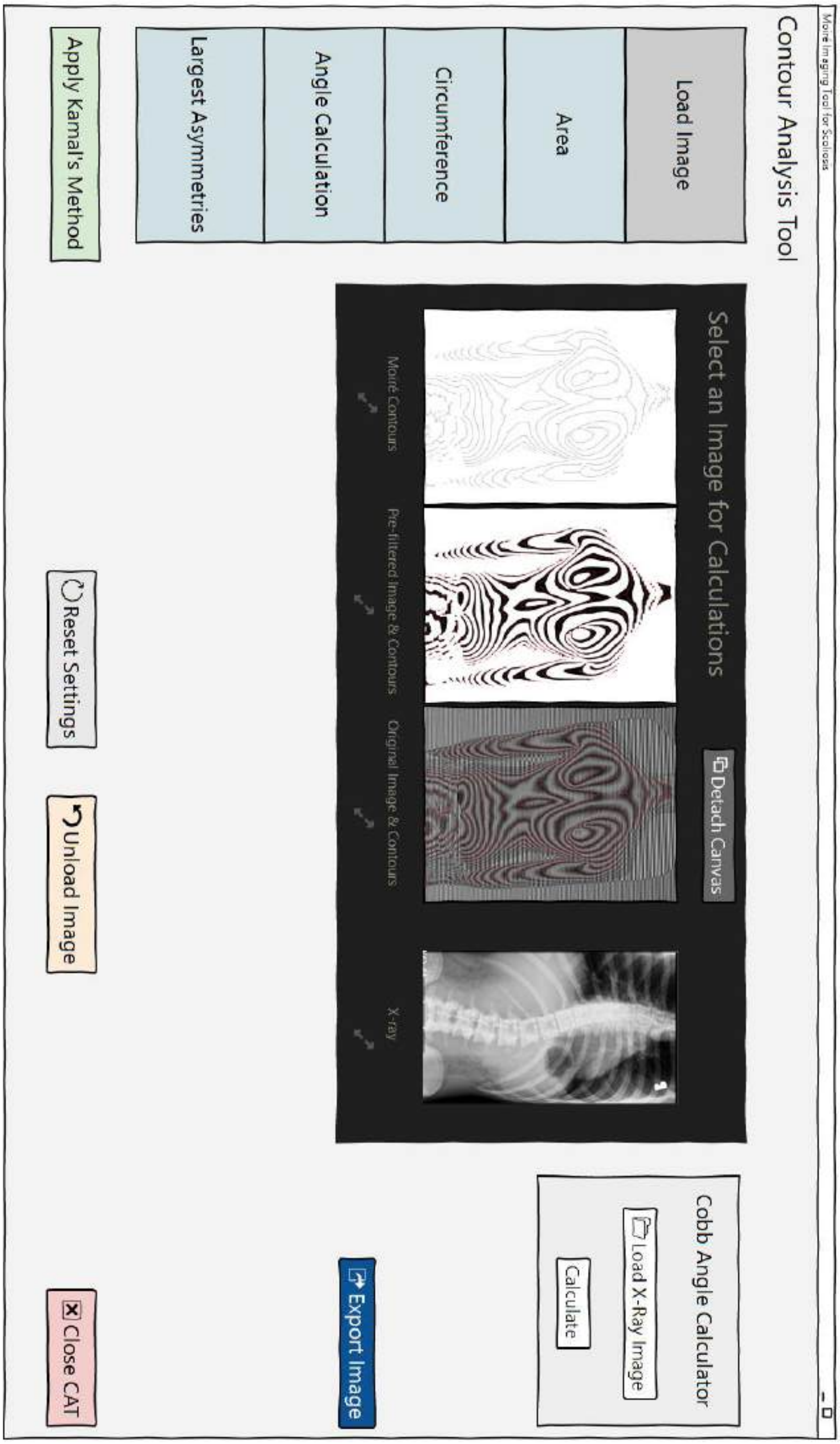
SD Value: 4.8

Repetition: 3

Repetition: Inf

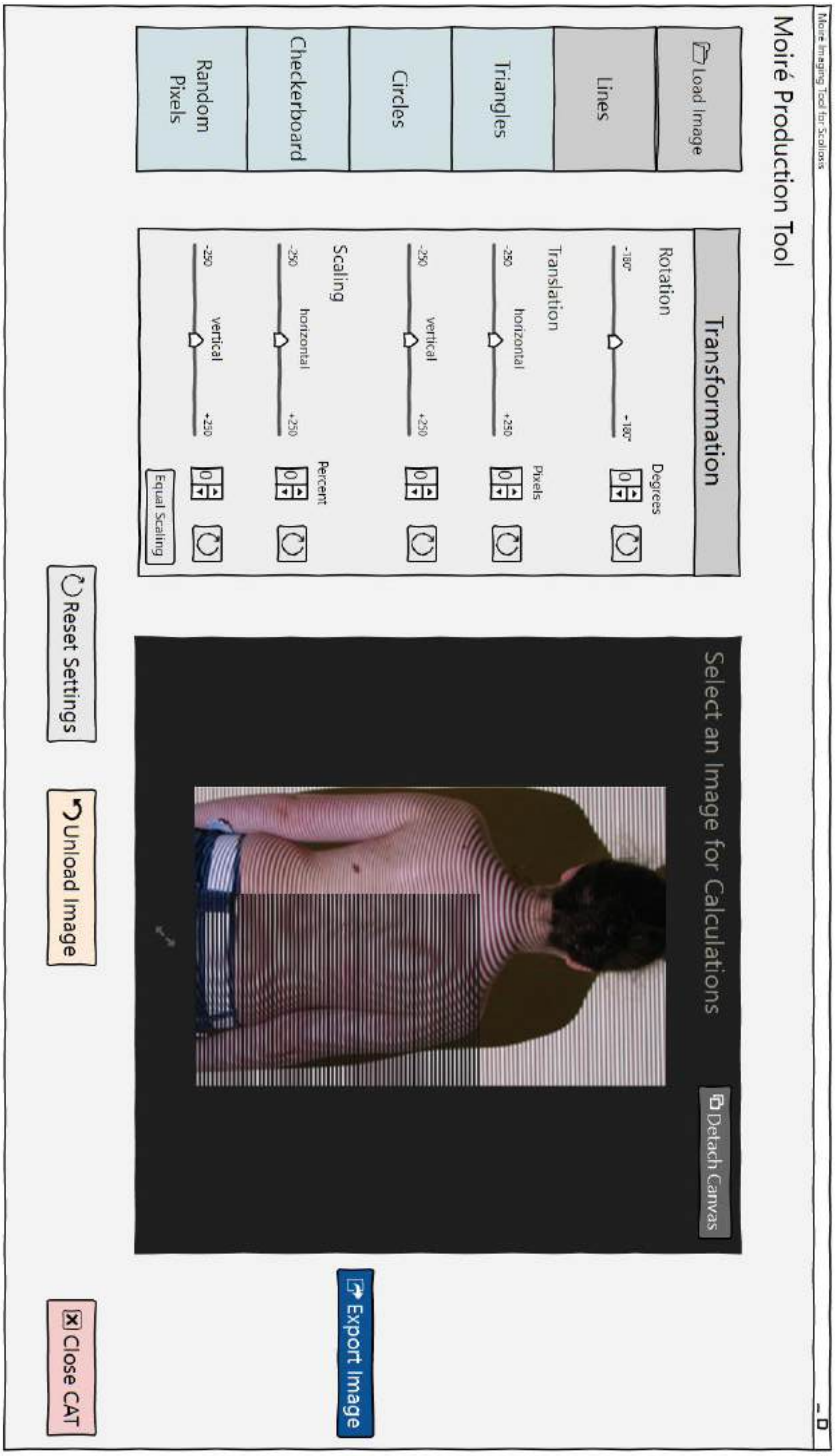
Appendix B: Concept Preview of Contour Analysis Tool

Screenshot captured in WireframeSketcher (14-day trial of v6.2.3)



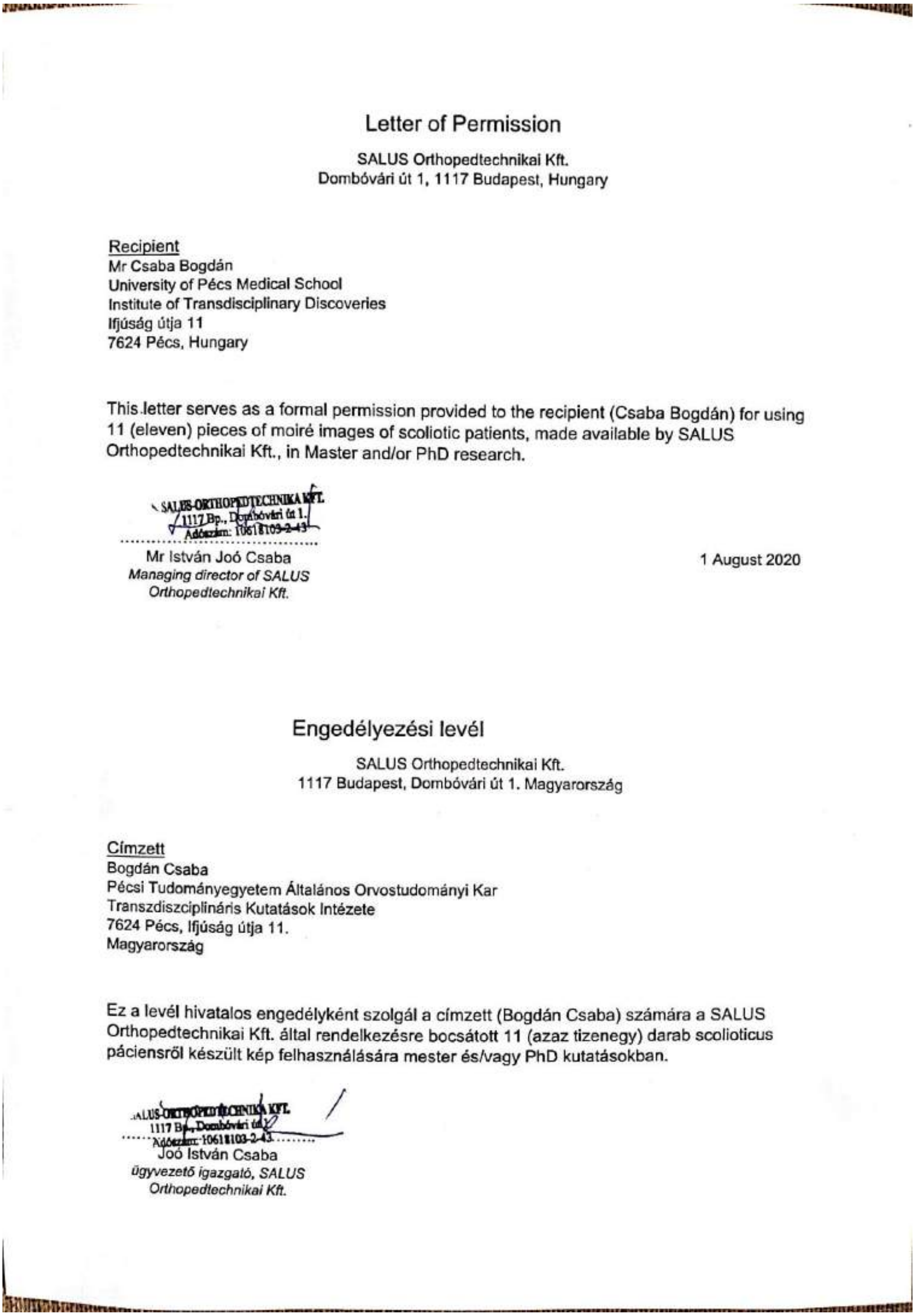
Appendix C: Concept Preview of Moiré Production Tool

Screenshot captured in WireframeSketcher (14-day trial of v6.2.3)



Appendix D: Letter of Permission for Using Moiré Images

Issued by SALUS Orthopedtechnikai Kft.



Letter of Permission

SALUS Orthopedtechnikai Kft.
Dombóvári út 1, 1117 Budapest, Hungary

<u>Recipient</u>
Mr Csaba Bogdán
University of Pécs Medical School
Institute of Transdisciplinary Discoveries
Ifjúság útja 11
7624 Pécs, Hungary

This letter serves as a formal permission provided to the recipient (Csaba Bogdán) for using 11 (eleven) pieces of moiré images of scoliotic patients, made available by SALUS Orthopedtechnikai Kft., in Master and/or PhD research.

SALUS-ORTHOPEDTECHNIKA KFT.
1117 Bp., Dombóvári út 1.
Adószám: 10618103-2-43

Mr István Joó Csaba
Managing director of SALUS Orthopedtechnikai Kft.

1 August 2020

Engedélyezési levél

SALUS Orthopedtechnikai Kft.
1117 Budapest, Dombóvári út 1. Magyarország

<u>Címzett</u>
Bogdán Csaba
Pécsi Tudományegyetem Általános Orvostudományi Kar
Transzdiszciplináris Kutatások Intézete
7624 Pécs, Ifjúság útja 11.
Magyarország

Ez a levél hivatalos engedélyként szolgál a címzett (Bogdán Csaba) számára a SALUS Orthopedtechnikai Kft. által rendelkezésre bocsátott 11 (azaz tizenegy) darab scolioticus páciensről készült kép felhasználására mester és/vagy PhD kutatásokban.

SALUS-ORTHOPEDTECHNIKA KFT.
1117 Bp., Dombóvári út
Adószám: 10618103-2-43

Joó István Csaba
ügyvezető igazgató, SALUS Orthopedtechnikai Kft.

Appendix E: Code of Static Moiré Fringe Segmenting Algorithm

Developed in MATLAB®. version 9.5.0.944444 (R2018b). Natick, Massachusetts: The MathWorks Inc.; 2018. (available via academic license, Fachhochschule Wiener Neustadt)

```
% Reading grayscale image for further processing and reference
        img = imread('image.jpg');
        imgoriginal = img;

% Enhancing contrast I
        img = imadjust(imadjust(imadjust(img)));

% Increasing brightness
        img = img + 120;

% Enhancing contrast II
        img = imadjust(img,[0.7 1]);

% Applying 2-D Gaussian filter
        img = imgaussfilt(img,6);

% Applying repeated dilation
        se = strel('square', 3); % defining structuring element
        img = imdilate(img,se);
        img = imdilate(img,se);
        img = imdilate(img,se);

% Applying thresholding
        img = imbinarize(img,0.41);

% Skeletonizing
        imgcompl = imcomplement(img);
        imgthin = bwmorph(imgcompl,'thin', Inf);
        imgthin = bwmorph(imgthin, 'fatten', 1);
        imgskel = im2uint8(imgthin);

% Visualizing
        figure(1)
          % Overlaying skeletonized image on thresholded one
               img = im2uint8(img); % for 'labeloverlay' that handles no logical types)
               imshow(labeloverlay(img,imgskel,'Transparency',0))
        figure(2)
          % Overlaying skeletonized image on original's grayscale
          imshow(labeloverlay(imgoriginal,imgskel,'Transparency',0))

% Saving figures in scalable .svg format
        saveas(figure(1),'contour_on_tresholded.svg')
        saveas(figure(2),'contour_on_grayscaled.svg')
```

Appendix F: Code of Adaptive Moiré Fringe Segmenting Algorithm

Developed in MATLAB®. version 9.5.0.944444 (R2018b). Natick, Massachusetts: The MathWorks Inc.; 2018. (available via academic license, Fachhochschule Wiener Neustadt)

```
% Reading image for further processing and reference

         imgoriginal = imread('image.jpg');
         img = im2double(rgb2gray(imgoriginal));
         [m n] = size(img); % Calculating image dimensions

% Enhancing contrast based on root mean square values

        contrastvalue = rms(img);
        imgcontrast = img;
        for i = 1:n
                imgcontrast(1:end, i) = imadjust(img(1:end, i),[0 (1-(contrastvalue(1,i)))]);
        end

% Applying 2D-Gaussian filter based on root mean square values

        imggauss = imgcontrast;
        st = 4;     % Step in the loop
        h = 4;      % Maximum horizontal and vertical distance from the current pixel of the loop

        for i = (st+1):(m-st)
            for j = (st+1):(n-st)
                % Experimental number for 2D-Gaussian filtering
                gaussvalue = 10*rms(rms(img((i-h):(i+h),(j-h):(j+h))));
                imggauss((i-h):(i+h),(j-h):(j+h)) = imgaussfilt(imgcontrast((i-h):(i+h),(j-h):(j+h)),
                'Padding', gaussvalue);
            end
        end

% Histogram equalization

        imghisteq = histeq(imggauss);

% Applying 2D-Gaussian filter based on peak signal-to-noise ratio

        imgpsnr = abs(psnr(imghisteq, img));
        imggauss2 = imgaussfilt(imghisteq, imgpsnr);

% Calculating global image threshold using Otsu's method

        imgtresh = imbinarize(imggauss2, 'global');

% Skeletonizing

        imgcompl = imcomplement(imgtresh);
        imgthin = bwmorph(imgcompl, 'thin', Inf);
        imgthin = bwmorph(imgthin, 'fatten', 1);
        imgskel = im2uint8(imgthin);

% Saving results by overlaying skeletonized and original images

        imgskelonoriginal = labeloverlay(imgoriginal, imgskel, 'Transparency', 0);
```

Digital Appendix

Digital Appendix written on DVD attached to this PhD dissertation
Also available in Google Drive until December 31, 2023: https://bit.ly/3ErXc99

Digital Appendix A: Results of Literature Review

Content: Results of literature review
Filename: DIGA_Results_of_Literature_Review_Csaba_Bogdán_UoP_PhD_Thesis.zip
Format: Compressed data types in a single .zip file: .txt, .ris, .nbib
Size: 72.9 KB

Compressed files:

IEEE_Xplore_Citation_Download_2022.04.30.ris
IEEE_Xplore_Citation_Download_2022.04.30.txt
PubMed_Citation_Download_2022.04.30.nbib
PubMed_Citation_Download_2022.04.30.txt
ScienceDirect_Citation_Download_2022.04.30.ris
ScienceDirect_Citation_Download_2022.04.30.txt

Digital Appendix B: Phases of Literature Review

Content: Phases of literature review
Filename: DIGB_Phases_of_Literature_Review.zip
Format: Compressed .txt data types in a single .zip file
Size: 40.8 KB

Compressed files:

Literature_Filter_1A_Removed_by_Duplicates.txt
Literature_Filter_1B_Removed_by_Time_Range_(before_1990).txt
Literature_Filter_2_Removed_by_Non-English_Titles.txt
Literature_Filter_3_Removed_by_Irrelevant_Titles.txt
Literature_Filter_4_Removed_by_Screening_Abstracts.txt
Literature_Filter_5A_Removed_by_Screening_Full_Text_Phase_1.txt
Literature_Filter_5B_Papers_Added_from_Citations.txt
Literature_Filter_5C_Removed_by_Screening_Full_Text_Phase_2.txt
Literature_Filter_6_Final_Papers_for_the_Review.txt

Digital Appendix C: Demo for the Prototype of Fringe Segmentation Tool

Content: Demo for the concept of Fringe Segmentation Tool
Filename: DIGC_Demo_of_Fringe_Segmentation_Tool_Csaba_Bogdán_PTE_PhD_Thesis.mp4
Format: .mp4 viedo file
Size: 35.7 MB
Audio: No
Length: 00:02:46 (HH:MM:SS.)
Resolution: 1368x800
Frame rate: 30.00 FPS

List of Tables

List of Figures

References

[1] Labecka MK, Plandowska M. Moiré topography as a screening and diagnostic tool-A systematic review. PLoS One. 2021;16(12):e0260858.

[2] Czaprowski D, Stoliński Ł, Tyrakowski M, Kozinoga M, Kotwicki T. Non-structural misalignments of body posture in the sagittal plane. Scoliosis Spinal Disord. 2018;13:6.

[3] Hawke F, Rome K, Evans AM. The relationship between foot posture, body mass, age and ankle, lower-limb and whole-body flexibility in healthy children aged 7 to 15 years. J Foot Ankle Res. 2016;9:14.

[4] Evans AM. The paediatric flat foot and general anthropometry in 140 Australian school children aged 7 - 10 years. J Foot Ankle Res. 2011;4(1):12.

[5] Martínez-Nova A, Gijón-Noguerón G, Alfageme-García P, Montes-Alguacil J, Evans AM. Foot posture development in children aged 5 to11 years: A three-year prospective study. Gait & Posture. 2018;62:280-4.

[6] Angarita-Fonseca A, Boneth-Collante M, Ariza-Garcia CL, Parra-Patiño J, Corredor-Vargas JD, Villamizar-Niño AP. Factors associated with non-specific low back pain in children aged 10-12 from Bucaramanga, Colombia: A cross-sectional study. J Back Musculoskelet Rehabil. 2019;32(5):739-47.

[7] Calvo-Muñoz I, Gómez-Conesa A, Sánchez-Meca J. Prevalence of low back pain in children and adolescents: a meta-analysis. BMC Pediatr. 2013;13:14.

[8] Filho JNdS, Batista LA, Gurgel JL, Porto F. Shadow Moiré technique for postural assessment: qualitative assessment protocol by intra- and inter-rater evaluation. Journal of Physical Therapy Science. 2017;29(2):356-60.

[9] Silva JG, Almeida MSd, Costa CGd, Rocha AF, Silva PMd, Silva RTGd, et al. Moiré topography: an alternative to scoliosis evaluation in student's health. Journal of Human Growth and Development. 2014;24:62-6.

[10] Negrini S, Donzelli S, Aulisa AG, Czaprowski D, Schreiber S, de Mauroy JC, et al. 2016 SOSORT guidelines: orthopaedic and rehabilitation treatment of idiopathic scoliosis during growth. Scoliosis Spinal Disord. 2018;13:3.

[11] Caruncho MV. The effects of diagnostic radiation. [Os efeitos da radiação diagnóstica]. Revista Brasileira de Medicina de Família e Comunidade. 2011;6(19):116-7. [Portuguese].

[12] Brent RL. Carcinogenic risks of prenatal ionizing radiation. Seminars in Fetal and Neonatal Medicine. 2014;19(3):203-13.

[13] Lin EC. Radiation risk from medical imaging. Mayo Clin Proc. 2010;85(12):1142-6; quiz 6.

[14] Knott P, Sturm P, Lonner B, Cahill P, Betsch M, McCarthy R, et al. Multicenter Comparison of 3D Spinal Measurements Using Surface Topography With Those From Conventional Radiography. Spine Deformity. 2016;4(2):98-103.

[15] Guidetti L, Bonavolontà V, Tito A, Reis VM, Gallotta MC, Baldari C. Intra- and Interday Reliability of Spine Rasterstereography. BioMed Research International. 2013;2013:745480.

[16] Zheng Y-P, Lee TT-Y, Lai KK-L, Yip BH-K, Zhou G-Q, Jiang W-W, et al. A reliability and validity study for Scolioscan: a radiation-free scoliosis assessment system using 3D ultrasound imaging. Scoliosis and spinal disorders. 2016;11(1):13.

[17] Lai KK-L, Lee TT-Y, Lee MK-S, Hui JC-H, Zheng Y-P. Validation of Scolioscan Air-Portable Radiation-Free Three-Dimensional Ultrasound Imaging Assessment System for Scoliosis. Sensors (Basel). 2021;21(8):2858.

[18] Kwok G, Yip J, Yick KL, Cheung MC, Tse CY, Ng SP, et al. Postural Screening for Adolescent Idiopathic Scoliosis with Infrared Thermography. Sci Rep. 2017;7(1):14431.

[19] Takasaki H. Moiré topography. Applied optics. 1970;9(6):1467-72.

[20] Porto F, Gurgel JL, Russomano T, Farinatti PDTV. Moiré topography: characteristics and clinical application. Gait & Posture. 2010;32(3):422-4.

[21] Batouche M, Benlamri R, editors. A computer vision system for diagnosing scoliosis. Proceedings of IEEE International Conference on Systems, Man and Cybernetics; 1994: IEEE.

[22] Kim HS, Ishikawa S, Ohtsuka Y, Shimizu H, Shinomiya T, Viergever MA. Automatic scoliosis detection based on local centroids evaluation on moire topographic images of human backs. IEEE transactions on medical imaging. 2001;20(12):1314-20.

[23] Porto F, Gurgel JL, Russomano T, Farinatti PT. Moiré Topography: From Takasaki Till Present Day. Recent Advances in Scoliosis: InTech Publications; 2012. p. 103-18.

[24] Ikeda T, Terada H. Development of the moiré method with special reference to its application to biostereometrics. Optics & Laser Technology. 1981;13(6):302-6.

[25] Kim H, Ushijima H, Ishikawa S, Otsuka Y, Shimizu H, Shinomiya T, et al., editors. Scoliosis detection based on difference of apexes position and angle on Moiré topographic images. International Congress Series; 2004.

[26] Balla P, Manhertz G, Antal A. Diagnostic moiré image evaluation in spinal deformities. Optica Applicata. 2016;46(3).

[27] Antal Á. Error analysis and identification of optically generated Moiré surfaces with use of measuring applications [Optikai úton generált Moiréfelületek hibaanalízise és identifikálása méréstechnikai alkalmazásokkal. [Doctoral dissertation, in Hungarian language]: Budapest University of Technology and Economics (Hungary); 2009.

[28] Zhi H, Johansson RB. Interpretation and classification of fringe patterns. Optics and lasers in engineering. 1992;17(1):9-25.

[29] Zhi H, Johansson R, editors. Interpretation and classification of fringe patterns. 11th IAPR International Conference on Pattern Recognition Vol III Conference C: Image, Speech and Signal Analysis; 1992: IEEE Computer Society.

[30] Takasaki H. Guest editorial. Moiré Topography in Japan. Optics and Lasers in Engineering. 1982;3(1):1-.

[31] Drazen B. Challenges Of Interdisciplinary Research. Interdisciplinary Management Research. 2010;6:951-60.

[32] Makerspace at the University: a Recommendation and Technical Assistance for the Integration of Makerspaces in Higher Education [Makerspace az egyetemen: Ajánlás és műszaki segédlet digitális közösségi alkotóműhelyek felsőoktatási integrációjához] (in Hungarian language). Pécs, Hungary: University of Pécs Medical School; 2022. 144 p.

[33] Petra B, Kata P, Ákos A. Evaluation of digital moiré pictures for following conditions of patients with spinal deformities [Digitális moiré képek vizsgálata gerincferdüléses betegek nyomon követésére]. (in Hungarian). Biomechanica Hungarica. 2014;7(1).

[34] Patias P, Grivas TB, Kaspiris A, Aggouris C, Drakoutos E. A review of the trunk surface metrics used as Scoliosis and other deformities evaluation indices. Scoliosis. 2010;5(12):20.

[35] Turner-Smith A, Harris J. ISIS-An automated shape measurement and analysis System. Proc of 3rd Int Symposium on Surface Topography and Spinal Deformity, 1986, September 27-28; Oxford: Gustav Fischer Verlag; 1984. p. 31-28.

[36] Pearsall DJ, Reid JG, Hedden DM. Comparison of three noninvasive methods for measuring scoliosis. Physical Therapy. 1992;72(9):648-57.

[37] Drerup B. A procedure for the numerical analysis of moiré topograms. Photogrammetria. 1981;36(2):41-9.

[38] Hamra A, Volpon JB. Fotopodometria" moiré" quantitativa na avaliaçäo do arco plantar longitudinal medial. Rev bras ortop. 1995:609-14.

[39] Kotwicki T, Negrini S, Grivas TB, Rigo M, Maruyama T, Durmala J, et al. Methodology of evaluation of morphology of the spine and the trunk in idiopathic scoliosis and other spinal deformities - 6th SOSORT consensus paper. Scoliosis. 2009;4(26):1748-7161.

[40] Elman C, Gerring J, Mahoney J. The Production of Knowledge: Enhancing Progress in Social Science: Cambridge University Press; 2020.

[41] Turner-Smith AR. A television/computer three-dimensional surface shape measurement system. Journal of biomechanics. 1988;21(6):515-29.

[42] Berryman F, Pynsent P, Fairbank J, Disney S. A new system for measuring three-dimensional back shape in scoliosis. European spine journal : official publication of the European Spine Society, the European Spinal Deformity Society, and the European Section of the Cervical Spine Research Society. 2008;17(5):663-72.

[43] Goldberg CJ, Kaliszer M, Moore DP, Fogarty EE, Dowling FE. Surface topography, Cobb angles, and cosmetic change in scoliosis. Spine. 2001;26(4):E55-E63.

[44] Groves D, Curran P, editors. An accurate, fast and cost effective method for the measurement of body shape and the assessment of spinal deformity. Proceedings of the 6th international symposium on surface topography and spinal deformity; 1992: Gustav Fischer Stuttgart.

[45] Oxborrow N. Assessing the child with scoliosis: the role of surface topography. Archives of disease in childhood. 2000;83(5):453-5.

[46] Drerup B, Hierholzer E. Back shape measurement using video rasterstereography and three-dimensional reconstruction of spinal shape. Clinical Biomechanics. 1994;9(1):28-36.

[47] Drerup B, Hierholzer E. Assessment of scoliotic deformity from back shape asymmetry using an improved mathematical model. Clinical Biomechanics. 1996;11(7):376-83.

[48] Frobin W, Hierholzer E. Video rasterstereography: a method for on-line measurement of body surfaces. Photogrammetric engineering and remote sensing. 1991;57(10):1341-5.

[49] Degenhardt B, Starks Z, Bhatia S, Franklin G-A. Appraisal of the DIERS method for calculating postural measurements: an observational study. Scoliosis and spinal disorders. 2017;12(1):1-11.

[50] Product-portfolio brochure of DIERS International GmbH (2015), Available from: https://diers.eu/wp-content/uploads/2016/05/DIERS_product-portfolio_brochure_EN.pdf [cited 02 May 2022].

[51] Batouche M, Benlamri R, Kholladi M. A computer vision system for diagnosing scoliosis using moiré images. Computers in Biology and Medicine. 1996;26(4):339-53.

[52] Wiklund ME, Wilcox SB. Designing usability into medical products: CRC Press; 2005.

[53] Bogdán C. The theory of the moiré method and its application in scoliosis [A moirémódszer és alkalmazásának elmélete scoliosisban] (in Hungarian) [Bachelor's thesis]: Institute of Mechatronics Engineering and Research (Zalaegerszeg, Hungary), University of Pannonia; 2018.

[54] Bogdán C. The Moiré Method and a Research Framework Concept Adapted to Moiré Imaging in Scoliosis [Master's thesis]: Fachhochschule Wiener Neustadt; 2020.

[55] Creath K, Wyant J. Moiré and fringe projection techniques. Optical shop testing. 1992;2:653-85.

[56] Conway A. Moiré fringes on the factory floor. New Scientist. 22 June 1972;54(801):692-4.

[57] Merriam-Webster. Webster’s ninth new collegiate dictionary: Springfield, Mass.: Merriam-Webster, 1987, 763.

[58] Oxford concise dictionary of English etymology. Shanghai Foreign Language Press; 2000.

[59] Turi Z, Wenzel K. Moiré-Methoden bei der Messung und Untersuchung der Oberflächengestalten, Gestaltfehler und Gestaltveränderungen. Periodica Polytechnica Mechanical Engineering. 1989;33(3):197-208.

[60] Amidror I. The Theory of the Moiré Phenomenon, Volume I: Periodic Layers, Sec. 6. Springer; 2009.

[61] Rossler T, Hrabovsky M, Pochmon M. Moiré methods for measurement of displacement and topography. Czechoslovak Journal of Physics. 2006;56(2):101-24.

[62] Theocaris PS. Moiré Fringes in Strain Analysis: Pergamon Press; 1969.

[63] Patorski K, Kujawinska M. Handbook of the moiré fringe technique: Elsevier, Amsterdam; 1993.

[64] Malacara D, Thompson BJ. Handbook of optical engineering: Marcel Dekker New York; 2001.

[65] Antal Á, Fekete RT. Quasi-interferometric shape analysis of vehicle body elements [Jármű karosszériaelemek kvázi-interferometrikus alakvizsgálata] (in Hungarian language). A jövő járműve. 2008(3-4):44-7.

[66] Palmer C, Loewen EG. Diffraction grating handbook. 6th ed: Newport Corporation; 2005.

[67] Rayleigh L. XII. On the manufacture and theory of diffraction-gratings. The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science. 1874;47(310):81-93 et 193-205.

[68] Walker CA. Handbook of moiré measurement: CRC Press; 2004.

[69] Righi A. Sui fenomeni che si producono colla sovrapposizione di due peticoli e sopra alcune loro applicazioni. Nuovo Cimento. 1887;21(1):203-28.

[70] Bogdán C. The moiré method and its application in scoliosis. In: Háber IE, Bogdán C, Szoke A, editors. Proceedings of 4th International Interdisciplinary 3D Conference. Pécs: Pécsi Tudományegyetem; 2018. p. 81-7.

[71] Kishen A, Asundi A. Fundamentals and applications of biophotonics in dentistry. London;Hackensack, NJ;: Imperial College Press; 2007.

[72] Tropea C, Yarin AL, Foss JF. Springer handbook of experimental fluid mechanics: Springer; 2007.

[73] Kanazawa E, Sekikawa M, Ozaki T. Three-dimensional Measurements of the Occlusal Surfaces of Upper Molars in a Dutch Population. Journal of dental research. 1984;63(11):1298-301.

[74] Kishen A, Asundi A. Investigations of thermal property gradients in the human dentine. Journal of Biomedical Materials Research: An Official Journal of The Society for Biomaterials, The Japanese Society for Biomaterials, and The Australian Society for Biomaterials and the Korean Society for Biomaterials. 2001;55(1):121-30.

[75] Raman C, Datta SK. On Brewster's bands. Part I. Transactions of the Optical Society. 1925;27(1):51-5.

[76] Tollenaar D. Moiré interferentieverschijnselen bij rasterdruck. Amsterdam, Institut voor graphische Technick. 1945.

[77] Merton T. Nouvelles méthodes de fabrication des réseaux. Journal de Physique et le Radium. 1952;13(2):49-53.

[78] Nishijima Y, Oster G. Moiré patterns: their application to refractive index and refractive index gradient measurements. JOSA. 1964;54(1):1-5.

[79] Tollenaar D. Moiré in halftone printing interference phenomena. In: Indebetouw G, Czarnek R, editors. Selected Papers on Optical Moiré and Applications. SPIE Milestone Series. 64: SPIE Optical Engineering Press; 1992. p. 618-33.

[80] Yule J. Moiré Patterns and Screen Angles, Chap. 13 in Yule, J. (auth) Principles of Color Reproduction: John Wiley & Sons; 1967. 328-45 p.

[81] Oster G, Wasserman M, Zwerling C. Theoretical interpretation of moiré patterns. JOSA. 1964;54(2):169-75.

[82] Harthong J. Le moiré. Advances in Applied Mathematics. 1981;2(1):24-75.

[83] Lohmann A, Paris D. Variable Fresnel zone pattern. Applied optics. 1967;6(9):1567-70.

[84] Bryngdahl O. Moiré: formation and interpretation. JOSA. 1974;64(10):1287-94.

[85] Bryngdahl O. Moiré and higher grating harmonics. JOSA. 1975;65(6):685-94.

[86] Legault R. The aliasing problems in two-dimensional sampled imagery. In: Biberman LM, editor. Perception of Displayed Information: Springer; 1973. p. 279-312.

[87] Steinbach A, Wong KY. Moire patterns in scanned halftone pictures. JOSA. 1982;72(9):1190-8.

[88] Takeda M, Ina H, Kobayashi S. Fourier-transform method of fringe-pattern analysis for computer-based topography and interferometry. JOSA. 1982;72(1):156-60.

[89] Morimoto Y, Seguchi Y, Higashi T. Application Of Moire Analysis Of Strain Using Fourier Transform. Optical Engineering. 1988;27(8):650-6.

[90] Takasaki H. Moiré topography. Applied optics. 1973;12(4):845-50.

[91] Takasaki H. The Development and the Present Status of Moiré Topography. Optica Acta: International Journal of Optics. 1979;26(8):1009-19.

[92] Lino ACL, Fabbro IMD. Fruit profilometry based on shadow Moiré techniques. Ciência e Agrotecnologia. 2004;28(1):119-25.

[93] Antal Á. Surface identification by moiré method [Felületazonosítás moirémódszerrel]. [An internal auxiliary guide on moiré measurements]. Budapest University of Technology and Economics. 2009.

[94] Kim H, Tan JK, Ishikawa S, Shinomiya T. Automatic detection of spinal deformity based on statistical features from the moire topographic images. International Journal of Computing. 2009;8(1):72-8.

[95] Paakkari J. On-line flatness measurement of large steel plates using moire topography. [dissertation on the internet]: Technical Research Centre of Finland, Espoo; 1998, retrieved from: https://www.vttresearch.com/sites/default/files/pdf/publications/1998/P350.pdf [cited 2021 December 11].

[96] Mínguez MF, Buendía M, Cibrián RM, Salvador R, Laguía M, Martín A, et al. Quantifier variables of the back surface deformity obtained with a noninvasive structured light method: evaluation of their usefulness in idiopathic scoliosis diagnosis. European Spine Journal. 2007;16(1):73-82.

[97] Lim JS, Kim J, Chung MS. Automatic shadow moiré topography: a moving-light-source method. Optics letters. 1989;14(22):1252-3.

[98] Lay Y-L, Yang H-J, Lin C-S, Chen W-Y. 3D face recognition by shadow moiré. Optics & Laser Technology. 2012;44(1):148-52.

[99] Cloud G. Optical methods of engineering analysis. Cambridge: Cambridge University Press. 1995.

[100] Jin L, Yoshizawa T. Moiré Metrology. In: Yoshizawa T, editor. Handbook of Optical Metrology. 2 ed: CRC Press; 2015. p. 273-98.

[101] Briers J. Holographic, speckle and moiré techniques in optical metrology. Progress in quantum electronics. 1993;17(3):167-233.

[102] Balla P, Manhertz G, Antal Á. Computerized evaluation of digital orthopedic moiré pictures. Recent Innovations in Mechatronics. 2014;1(1-2).

[103] Hovanesian JD, Hung YY. Moiré contour-sum contour-difference, and vibration analysis of arbitrary objects. Applied Optics. 1971;10(12):2734-38.

[104] Idesawa M, Yatagai T, Soma T. Scanning moiré method and automatic measurement of 3-D shapes. Applied Optics. 1977;16(8):2152-62.

[105] Drajkó A, J. Kocsis Á, Tamás P, Antal Á. Analyzing spinal deformities by spatial data extracted from computer generated moiré images. Biomechanica Hungarica. 2013;6(1):323-9.

[106] Kodera Y, Jin L, Otani Y, Yoshizawa T. Shadow Moiré Profilometry using Phase Shifting Method. Journal of the Japan Society for Precision Engineering. 1999;65:1456-60.

[107] Degrieck J, Van Paepegem W, Boone P. Application of digital phase-shift shadow moiré to micro deformation measurements of curved surfaces. Optics and Lasers in Engineering. 2001;36(1):29-40.

[108] Jin L, Otani Y, Yoshizawa T. Shadow moiré profilometry by frequency sweeping. Optical Engineering. 2001;40(7):1383-6.

[109] Kim S-W, Oh J-T, Jung M-S, Choi Y-B, editors. Two-frequency phase-shifting projection moire topography. Three-Dimensional Imaging, Optical Metrology, and Inspection IV; 1998: International Society for Optics and Photonics.

[110] Chen L-C, Tsai L-H. Dual phase-shifting moiré projection with tunable high contrast fringes for three-dimensional microscopic surface profilometry. Physics Procedia. 2011;19:67-75.

[111] Paveleva D. Colour moiré phenomenon and its application for topographical measurements [Doctoral dissertation]: Budapest University of Technology and Economics (Hungary); 2015, retrieved from:
https://repozitorium.omikk.bme.hu/bitstream/handle/10890/791/ertekezes.pdf?sequence=1&isAllowed=y [cited 2021 December 12].

[112] Kamal S. Measurement of angle of spinal curvature by moiré topographs. Journal of Islamic Medical Association (USA). 1982;14:145-9.

[113] Chalupová M. Use of a biomechanical model of the scapula region for the identification of muscle disbalance. 2001. Vol No. Paper is no more available via <mms.tudelft.nl/dsg/intersg/Proceedings_2001_files/06_chalupova.pdf> (cited by Porto F, Gurgel JL, Russomano T, Farinatti PT. Moiré Topography: From Takasaki Till Present Day. Recent Advances in Scoliosis: InTech Publications; 2012. p. 103-18.).

[114] Nagashima S, Tsutsumi E, Suzuki K, Ashizawa K, Isoda H. Generation of surface model of human trunk and its applications. Journal of human ergology. 1983;12(1):27-38.

[115] Moga P, Cloud GL. A Study of Scapular Displacement by Differential Moire Methods. Proc Spring 1991 Conference on Experimental Mechanics, Soc for Exp Mech; Milwaukee, WI (June 1991).

[116] Post D, Han B, Ifju P. Moiré Interferometry. High Sensitivity Moiré: Experimental Analysis for Mechanics and Materials. New York, NY: Springer US; 1994. p. 135-226.

[117] Wood J, Saha S, Rao R, Grillo D. Non-homogenous Strain Distributions in Bone Using Moiré Interferometry. Society for Experimental Mechanics, Portland, Oregon. 2001:989-92.

[118] Wood JD, Wang R, Weiner S, Pashley DH. Mapping of tooth deformation caused by moisture change using moire interferometry. Dental Materials. 2003;19(3):159-66.

[119] Wood JD, Brougher J. Deformation studies of bone and teeth using moiré interferometry. Society for Experimental Mechanics, Milwaukee, Wisconsin (June 2002), Session 47, Paper #238. 2002.

[120] Takasaki H. Moiré topography from its birth to practical application. Optics and lasers in engineering. 1982;3(1):3-14.

[121] Yeras AM, Peña RG, Junco R. Moiré topography: alternative technique in health care. Optics and Lasers in Engineering. 2003;40(1-2):105-16.

[122] Hertz H, Russomano T, Porto F, Steiger A, de Azevedo DF, Gurgel J. Development of shadow Moiré technique as an alternative low-cost method for postural evaluation. Scientia Medica. 2005;15(4):235-42.

[123] Hertz H. Construction and calibration of the shadow moiré technique for postural analysis [doctoral thesis]. Porto Alegre: Pontifical Catholic University (PUCRS). 2005.

[124] Castro S. A comparison of two postural assessment techniques in elderly of Porto Alegre and their level of physical activity [thesis]. Porto Alegre: Pontifical Catholic University (PUCRS). 2007.

[125] Dzielinski A, Skoneczny S, Zbikowski R, Kuklinski S. Cellular neural network application to Moiré pattern filtering. IEEE International Workshop on Cellular Neural Networks and their Applications; Budapest, Hungary: IEEE; 1990. p. 139-48.

[126] Uetake T, Ohtsuki F, Tanaka H, Shindo M. The vertebral curvature of sportsmen. Journal of Sports Sciences. 1998;16(7):621-8.

[127] Domagalska-Szopa M, Szopa A. Postural orientation and standing postural alignment in ambulant children with bilateral cerebral palsy. Clinical Biomechanics. 2017;49:22-7.

[128] Porto F, Gurgel JL, Russomano T, Farinatti PdTV. Shadow Moire Technique to measure deformity of the trunk surface in the elderly: a population-based study. Scoliosis: causes, symptoms and treatment New York: Nova Science Publishers. 2012:73-90.

[129] Jelen K, Kusová S. Pregnant Women: Moiré Contourgraph and it's Semiautomatic and Automatic Evaluation. Neuro endocrinology letters. 2004;25(1-2):52-6.

[130] Asundi A. Shadow-Moire Method for Foot-Pressure Measurement. Experimental Techniques. 1986;10(2):28-.

[131] Mrozkowiak M. Description of foot longitudinal arch burdened with its weight on the basis of female population at the age between 4 and 18 in the light of projection moiré. In: Rutkowska E, editor. Wellness and success in sport: Wydawnictwo Neurocentrum; 2009. p. 109-14.

[132] Katsuki T, Goto M, Kawano Y, Tashiro H, Kurata F. Numerization of symmetry of the nose using an analysis of moire-photograph of the face. Journal of Japanese Cleft Palate Association. 1980;5(2):145-53.

[133] Katsuki T, Goto M, Kawano Y, Tashiro H. Quantification of the Symmetry of the Nose Using an Analysis of Moire Photographs of the Face. Optics in Biomedical Sciences: Springer; 1982. p. 266-9.

[134] Takei T, Yokosawa S, Innami T, Miyazawa T, Kuwana T, Takagi M, et al. Application of moiré topography to forensic odontology. The Journal of Nihon University School of Dentistry. 1985;27(2):87-104.

[135] Kishen A, Asundi A. Experimental investigation on the role of water in the mechanical behavior of structural dentine. Journal of Biomedical Materials Research Part A: An Official Journal of The Society for Biomaterials, The Japanese Society for Biomaterials, and The Australian Society for Biomaterials and the Korean Society for Biomaterials. 2005;73(2):192-200.

[136] Kishen A, Asundi A. Photomechanical investigations on the stress-strain relationship in dentine macrostructure. Journal of Biomedical Optics. 2005;10(3):034010-0340111.

[137] Carvalho L, Roriz P, Simões J, Frazão O. New trends in dental biomechanics with photonics technologies. Applied Sciences. 2015;5(4):1350-78.

[138] Wang R, Weiner S. Strain–structure relations in human teeth using Moiré fringes. Journal of biomechanics. 1997;31(2):135-41.

[139] Wouters F, Jon-And C, Abramson N, Olsson L, Frithiof L, Soder P-Ö, et al. Measurement of gingival swelling from dental casts by generation of a moiré pattern with laser light. Journal of dental research. 1988;67(8):1118-21.

[140] Szabolcs M, János S, Zoltán C. Treatment of spinal deformity before Nicolas Andry [A gerincdeformitás kezelése Nicolas Andry előtt] (in Hungarian language). Biomechanica Hungarica. 2011;4(1):61-6.

[141] Illés T, Lakatos J, Varga PP. The diseases of the spine [A gerinc betegségei] (in Hungarian language). In: Szendrői M, editor. Ortopédia. 2nd ed: Semmelweis; 2009. p. 213-71.

[142] Janumala T, Ramesh K. A review of different analysing methods to detect spinal deformity. International Journal of Advanced Research in Computer and Communication Engineering. 2015;4(8):352-5.

[143] Greiner KA. Adolescent idiopathic scoliosis: radiologic decision-making. American family physician. 2002;65(9):1817-22.

[144] Kamal SA. Determination of degree of correction of spinal deformity by moire topographs. Moire Fringe Topography and Spinal Deformity. In: Drerup B, Frobin W, Hierholzer E, editors. Proceedings of the 2nd International Symposium September 12-15, 1982 Münster, West Germany: Gustav Fischer Verlag, Stuttgart; 1983. p. 117-26.

[145] Hulley SB, Newman TB, Cummings SR. Choosing the study subjects: specification, sampling, and recruitment. In: B. HS, R. CS, S. BW, G. GD, B. NT, editors. Designing Clinical Research. 4th ed: Wolters Kluwer Health; 2013. p. 23-31.

[146] Adair I, Van Wijk M, Armstrong G. Moiré topography in scoliosis screening. Clinical orthopaedics and related research. 1977;129:165-71.

[147] Cline HE, Lorensen WE, Holik AS. Automatic moire contouring. Applied optics. 1984;23(10):1454-9.

[148] Woo WH, Yen KS. Moiré Fringe Segmentation Using Fuzzy Inference System. In: Ibrahim H, Iqbal S, Teoh S, Mustaffa M, editors. 9th International Conference on Robotic, Vision, Signal Processing and Power Applications Lecture Notes in Electrical Engineering; Singapore: Springer; 2017. p. 247-55.

[149] MATLAB. (2018). 9.5.0.944444 (R2018b). Natick, Massachusetts: The MathWorks Inc.

[150] Ashvins Group White Paper: Designing Resourceful GUIs for Healthcare Applications. . Retrieved from: http://ashvinsgroup.com/Press/Publications/DesigningResourcefulGUIsForHealthcareApps.pdf [cited 12 December 2021].

[151] Galitz WO. The essential guide to user interface design: an introduction to GUI design principles and techniques. 3rd ed. Indianapolis, IN: Wiley Pub; 2007.

[152] Zarestky J, Cole CS. Strengths, opportunities, aspirations, and results: An emerging approach to organization development. New horizons in adult education & human resource development. 2017;29(1):5-19.

[153] Vohland K, Land-Zandstra A, Ceccaroni L, Lemmens R, Perelló J, Ponti M, et al. The science of citizen science: Springer Nature; 2021.

[154] Wiggins A, Wilbanks J. The Rise of Citizen Science in Health and Biomedical Research. The American Journal of Bioethics. 2019;19(8):3-14.

[155] Hargitai EG, Bogdán C, Sik A, Samoczi A, Hathazi M. Bottom-Up and Reciprocal Citizen Science: Untapped Resources of Novel Ideas. Preliminary Experiences of a Citizen Science As Public Engagement Program. Lusophone Journal of Cultural Studies. 2022;9(2):119-35.

[156] Bogdán C, Magony AD, Wolgang B, Antal Á, Tunyogi-Csapó M. Segmentation of moiré fringes of scoliotic spines using filtering and morphological operations. Acta Polytechnica Hungarica. 2023;20(2):223-41.

[157] Otsu N. A Threshold Selection Method from Gray-Level Histograms. IEEE Transactions on Systems, Man, and Cybernetics. 1979;9(1):62-6.

List of Publications

Publications related to the present dissertation

Research papers

Bogdán C, Magony AD, Wolgang B, Antal Á, Tunyogi-Csapó M. Segmentation of moiré fringes of scoliotic spines using filtering and morphological operations. Acta Polytechnica Hungarica, 2023, 20(2):223-241. **Impact Factor: 1.711 | Rank: Q2**
DOI: being currently generated.

Bogdán C, Magony AD, Hargitai EG, Antal Á, Tunyogi-Csapó M. Software-based segmentation of moiré images of scoliotic spine [Scolioticus gerinc moiréfelvételeinek szoftveres szegmentációja] (in Hungarian language). Biomechanica Hungarica, 2022, 15(2):7-21.
DOI: 10.17489/biohun/2022/2/558

Hargitai EG, Bogdán C, Sík A, Sámóczi A, Hatházi M. Bottom-Up and Reciprocal Citizen Science: Untapped Resources of Novel Ideas. Preliminary Experiences of a Citizen Science As Public Engagement Program. Lusophone Journal of Cultural Studies (LJCS), 2022, 9(2):119-135.
DOI: https://doi.org/10.21814/rlec.3996

Conference proceedings

Bogdán C. The moiré method and its application in scoliosis. In: Háber IE, Bogdán C, Szoke A (eds). Proceedings of 4th International Interdisciplinary 3D Conference. Pécs, Hungary: University of Pécs, 2018. p. 81-7. ISBN: 9789634292678

Bogdán C. Moiré Fringe Segmentation Tool: a software-based prototype for the detection of moiré fringes of scoliotic spine [Moiré Fringe Segmentation Tool: szoftveralapú prototípus a scolioticus gerinc moirésávjainak detektálásához] (in Hungarian language). In: Kajos LF, Bali C, Puskás T, Szabó R (eds). 11th Interdisciplinary Doctoral Conference 2022 Conference Book, Pécs, Hungary: Doctoral Student Association of the University of Pécs, 2022, 88-99. ISBN: 9789636260705.

Abstracts

Bogdán C. A Software-based Segmentation of Moiré Fringes of Scoliotic Spines. In: Halász R, Zimmermann I (eds). Abstract Book of the 1st International Conference of Biomedical Engineering and Innovation (24-26 Oct 2022, Pécs, Hungary), 20. ISBN: 97896362605382022
Available: https://icbei.pte.hu/assets/doc/icbei_abstract_book.pdf [Accessed: 07 Nov. 2022]

Bogdán C. Moiré Fringe Segmentation Tool: a Software-based Prototype for Detection of Moiré Fringes of Scoliotic Spines. In: Kajos LF, Bali C, Puskás T, Horváth-Polgár PI, Glázer-Kniesz A, Tislér Á, Kovács E (eds). 11th Interdisciplinary Doctoral Conference 25-26th of November 2022. Pécs, Hungary: Doctoral Student Association of the University of Pécs, 2022, 134. ISBN: 9789636260699
Available: https://dok.pte.hu/sites/dok.pte.hu/files/files/Kiadvanyok/Book_of_Abstracts_2022.pdf [Accessed: 08 Feb. 2023]

Edited books

Bogdán C, Hargitai EG (eds). Makerspace at the University: a Recommendation and Technical Assistance for the Integration of Makerspaces in Higher Education [Makerspace az egyetemen: Ajánlás és műszaki segédlet digitális közösségi alkotóműhelyek felsőoktatási integrációjához] (in Hungarian language). Pécs, Hungary: University of Pécs Medical School; 2022. 144 p. ISBN: 9789637178740.

Book chapters

Bogdán C. Technical Recommendation for Creating University-organized Makerspaces [Műszaki ajánlás egyetemi szervezésű makerspace-ek létrehozásához]. (in Hungarian language) In: Bogdán C, Hargitai EG (eds). Makerspace az egyetemen: Makerspace at the University: a Recommendation and Technical Assistance for the Integration of Makerspaces in Higher Education [Ajánlás és műszaki segédlet digitális közösségi alkotóműhelyek felsőoktatási integrációjához]. Pécs, Hungary: University of Pécs Medical School; 2022. p. 62-108., ISBN: 9789637178740.

Bogdán C, Hargitai EG. Makerspace at the University: a Recommendation for the Integration of Makerspaces in Higher Education [Makerspace az egyetemen. Ajánlás digitális közösségi alkotóműhelyek felsőoktatásba történő integrációjához]. (in Hungarian language) In: Bogdán C, Hargitai EG (eds). Makerspace at the University: a Recommendation and Technical Assistance for the Integration of Makerspaces in Higher Education [Makerspace az egyetemen: Ajánlás és műszaki segédlet digitális közösségi alkotóműhelyek felsőoktatási integrációjához]. Pécs, Hungary: University of Pécs Medical School; 2022. p. 32-50. ISBN: 9789637178740.

Oral presentations

Bogdán C. The moiré method and its application in scoliosis. In 4th International Interdisciplinary 3D Conference Engineering Section, Pécs, Hungary, 6 October 2018.

Bogdán C. A Software-based Segmentation of Moiré Fringes of Scoliotic Spines. In: 1st International Conference of Biomedical Engineering and Innovation (24-26 Oct 2022, Pécs, Hungary), Pécs, Hungary, 26 October 2022.

Bogdán C. Moiré Fringe Segmentation Tool: a Software-based Prototype for Detection of Moiré Fringes of Scoliotic Spines. In: 11th Interdisciplinary Doctoral Conference 25-26th of November 2022. Pécs, Hungary, 25 November 2022

Poster presentations

Bogdán C. The moiré method and its application in scoliosis (poster). In: Háber I. E., Bogdán C., Szőke A (eds). Proceedings of 4th International Interdisciplinary 3D Conference. Pécs, Hungary, 5-6 October 2018, University of Pécs, 2018, 115. ISBN: 9789634292678

Editor of conference proceedings

Háber I. E., Bogdán C., Szőke A (eds). Proceedings of 4th International Interdisciplinary 3D Conference: Engineering Section, Pécs, Hungary, October 5-6, 2018, ISBN: 9789634292678, Available: https://pte3d.hu/konferencia/assets2/doc/Proceedings_4th-3D-Conf-2018.pdf [cited 2022 April 23].

Academic theses

Bogdán C. The theory of the moiré method and its application in scoliosis [A moirémódszer és alkalmazásának elmélete scoliosisban] [Bachelor's thesis] (in Hungarian language): Institute of Mechatronics Engineering and Research (Zalaegerszeg, Hungary), University of Pannonia; 2018.

Bogdán C. The Moiré Method and a Research Framework Concept Adapted to Moiré Imaging in Scoliosis [Master's thesis]: Fachhochschule Wiener Neustadt; 2020.

Publications not related to the present dissertation

Book chapters

Bogdán C. Makerspace and its relatives - a terminological summary [A makerspace és rokonai - terminológiai összefoglaló]. (in Hungarian language) In: Bogdán C, Hargitai EG (eds). Makerspace at the University: a Recommendation and Technical Assistance for the Integration of Makerspaces in Higher Education [Makerspace az egyetemen: Ajánlás és műszaki segédlet digitális közösségi alkotóműhelyek felsőoktatási integrációjához]. Pécs, Hungary: University of Pécs Medical School; 2022. p. 10-11. ISBN: 9789637178740.

Bogdán C. Makerspace as a scene of prototyping, education and innovation [A makerspace mint a prototípusgyártás, oktatás és innováció színtere]. (in Hungarian language) In: Bogdán C, Hargitai EG (eds). Makerspace at the University: a Recommendation and Technical Assistance for the Integration of Makerspaces in Higher Education [Makerspace az egyetemen: Ajánlás és műszaki segédlet digitális közösségi alkotóműhelyek felsőoktatási integrációjához]. Pécs, Hungary: University of Pécs Medical School; 2022. p. 8-9. ISBN: 9789637178740.

Bogdán C, Hargitai EG. Guarantees of the sustainability of makerspaces [Az alkotótér fenntarthatóságának biztosítékai]. (in Hungarian language) In: Bogdán C, Hargitai EG (eds). Makerspace at the University: a Recommendation and Technical Assistance for the Integration of Makerspaces in Higher Education [Makerspace az egyetemen: Ajánlás és műszaki segédlet digitális közösségi alkotóműhelyek felsőoktatási integrációjához]. Pécs, Hungary: University of Pécs Medical School; 2022. p. 132-135. ISBN: 9789637178740.

Bogdán C. The basics of makerspace design [A makerspace tervezésének alapvetései]. (in Hungarian language) In: Bogdán C, Hargitai EG (eds). Makerspace at the University: a Recommendation and Technical Assistance for the Integration of Makerspaces in Higher Education [Makerspace az egyetemen: Ajánlás és műszaki segédlet digitális közösségi alkotóműhelyek felsőoktatási integrációjához]. Pécs, Hungary: University of Pécs Medical School; 2022. p. 58-60. ISBN: 9789637178740.

Bogdán C, Hargitai EG. Conceptualization of higher education makerspaces [Felsőoktatási makerspace-ek koncepcionálása]. (in Hungarian language) In: Bogdán C, Hargitai EG (eds). Makerspace at the University: a Recommendation and Technical Assistance for the Integration of Makerspaces in Higher Education [Makerspace az egyetemen: Ajánlás és műszaki segédlet digitális közösségi alkotóműhelyek felsőoktatási integrációjához]. Pécs, Hungary: University of Pécs Medical School; 2022. p. 52-57. ISBN: 9789637178740.

Academic theses

Bogdán C. Ancient antisemitism (5th century BC-1st century AD) [Ókori zsidóellenesség (Kr.e. 5. sz.- Kr.u. 1.sz)] [Master's thesis] (in Hungarian language): Institute of History, Faculty of Humanities and Social Sciences, University of Szeged; 2010.

Bogdán C. Flavius Josephus and the slanderers of the Jews [Josephus Flavius és a zsidók rágalmazói] [Bachelor's thesis] (in Hungarian language): Department of Classica-Philology, Faculty of Humanities and Social Sciences, University of Szeged; 2010.

Text of publications related to the present dissertation

Research papers relevant to the dissertation are attached at the end of the thesis.

Selected works for attachment are as listed below:

Bogdán C, Magony AD, Wolgang B, Antal Á, Tunyogi-Csapó M. Segmentation of moiré fringes of scoliotic spines using filtering and morphological operations. Acta Polytechnica Hungarica, 2023, 20(2):223-241.

Bogdán C, Magony AD, Hargitai EG, Antal Á, Tunyogi-Csapó M. Software-based segmentation of moiré images of scoliotic spine [Scolioticus gerinc moiréfelvételeinek szoftveres szegmentációja] (in Hungarian language). Biomechanica Hungarica, 2022, 15(2):7-21.
DOI: 10.17489/biohun/2022/2/558

Hargitai EG, Bogdán C, Sík A, Sámóczi A, Hatházi M. Bottom-Up and Reciprocal Citizen Science: Untapped Resources of Novel Ideas. Preliminary Experiences of a Citizen Science As Public Engagement Program. Lusophone Journal of Cultural Studies (LJCS), 2022, 9(2):119-135.
DOI: https://doi.org/10.21814/rlec.3996

Segmentation of Moiré Fringes of Scoliotic Spines Using Filtering and Morphological Operations

Csaba Bogdán[1], Andor Dániel Magony[1], Wolfgang Birkfellner[2], Ákos Antal[3], Miklós Tunyogi-Csapó[4]

[1] Institute of Transdisciplinary Discoveries, Medical School, University of Pécs, Ifjúság útja 11, H-7624 Pécs, Hungary; csaba.bogdan@pte.hu; magony.andor@pte.hu

[2] Center for Medical Physics and Biomedical Engineering, Medical University of Vienna Spitalgasse 23, A-1090 Vienna, Austria; wolfgang.birkfellner@meduniwien.ac.at

[3] Department of Mechatronics, Optics and Mechanical Engineering Informatics, Budapest University of Technology and Economics, Bertalan Lajos u. 4-6, H-1111, Budapest, Hungary; akos@mogi.bme.hu

[4] National Center for Spinal Disorders, Buda Health Center, Királyhágó u. 1-3, H-1126 Budapest, Hungary; miklos.tunyogi@bhc.hu

---

Abstract: For reducing uncertainties in moiré pattern analysis, an accurate segmentation of moiré fringes (MF) is vital. In this study, an algorithm for segmenting MFs of scoliotic spines was provided in MATLAB® environment by an empirically established sequence of filtering and morphological operations defined by static function parameters: (1) contrast enhancement, (2) brightness increase, (3) contrast refinement, (4) 2-D Gaussian filter, (5) dilation, (6) thresholding, (7) skeletonization. The algorithm is simple, fast to process and, for the most part of the images, follows the MFs correctly. Further research on segmenting MFs is quite promising by improving the algorithm with adaptive and dynamic solutions, and exploring ways to replace time demanding and complex image processing techniques.

Keywords: moiré fringe segmentation; moiré method; shadow moiré; projection moiré; digital moiré; scoliosis

---

1 Introduction

Diagnosing spinal deformities has long been in the focus of medicine. Measurement of bending disorders of the vertebral column, such as scoliosis, is usually performed on radiographs by calculating the Cobb angle. 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, that can lead to fast, cost-effective and non-ionizing diagnostic imaging of the spine.

The phenomenon of moiré [mwaʁe] or moiré effect was elevated to scientific status, first, by Lord Rayleigh dealing with diffraction gratings in 1874 [1]. Lord Rayleigh concluded that moiré might be made useful for measurement purposes. About 100 years later, beyond industrial applications, further research proposed moiré topography for measurement of the human body [2], [3]. From the 1980s, MT is used on the whole human body, including oral cavity [4], bones [5], teeth and the skeletal system [6].

Moiré refers to an irregular wavy surface the pattern of which changes in accordance with its movement and can be observed, if two or more structures with similar geometry (nearly identical arrays of lines or dots) overlap, producing alternating bright and dark fringes (Fig. 1). Usually, dark fringes are called moiré fringes (MFs) or moiré stripes, but we can also consider bright ones as moiré surfaces when examining moiré images (MIs)—it is only a matter of agreement [7]. Based on the physical phenomenon of moiré, moiré techniques are defined as a group of methods usually used for surface mapping and shape or deformation measurement. In the scientific literature, shadow moiré and projection moiré techniques (SMT and PMT, respectively) seem to be the two primary methods of MT used for measurement of the human body (Fig. 2-3) [8].

An algorithm based on MT that proved to be suitable for calculating the curvature angle of the spine, may complement or substitute X-ray images–especially in follow-up examinations. The workload required for segmentation and evaluation of MIs is, however, not inconsiderable; some researchers see the best solution for that in an automatic system [8], [9], [10], [11], [12], [13]. And yet, processing of MIs requires several unique solutions that are especially influenced by optical arrangement, applied illumination (effect on intensity distribution), nature of noise and detection. Therefore, implementing a fully automated image analysis is a challenging, nevertheless desired objective in the field [7], [14]. For reducing uncertainties in moiré pattern analysis, an accurate segmentation of MFs is vital. The present study aims to contribute to the segmenting phase of MI analysis of scoliotic spines by providing an algorithm of filtering and morphological operations. This study presents the initial phase of the research, where static function parameters were applied to identify a possible segmenting sequence for MFs. Segmentation with adaptive and dynamic function parameters is not the subject of the present study but can be expected in a later phase of the research.

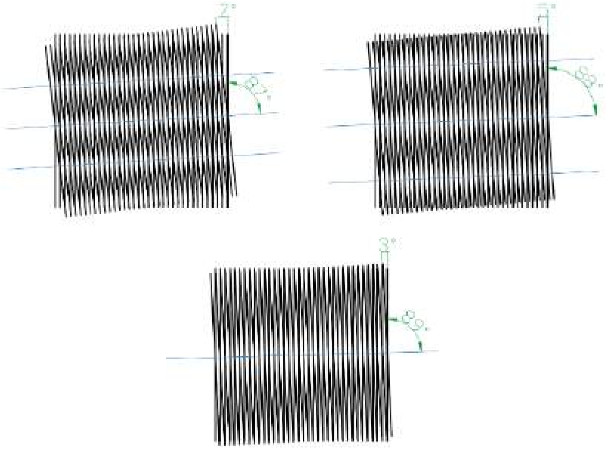


Figure 1
Moiré fringes of identical grids with different angle deviations

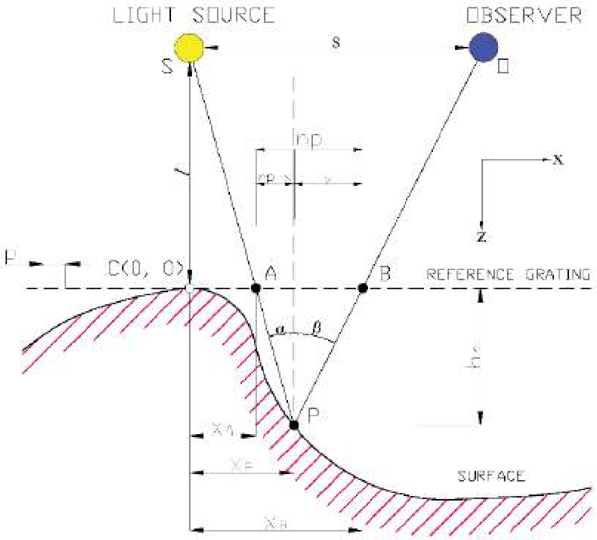


Figure 2
The base principle of shadow moiré technique

(A) Point where source light S passes through the reference grating
(B) Point where reflected source light S passes through the reference grating
(C) Origin
(O) Observer
(p) Grating pitch (or period of the grating)
(P) Measured point
(S) Light source

(α)	Incidence angle (of incoming light)
(β)	Viewing angle
(h_n)	Depth of n^{th}-order moiré pattern measured from the reference grating
(l)	Distance of S and O from the reference grating surface
(n)	Order of the moiré pattern
(s)	Interseparation of S and O
(X_A)	X component of SA distance
(X_B)	X component of SB distance
(X_P)	X component of SP distance
(x)	X component of PB distance

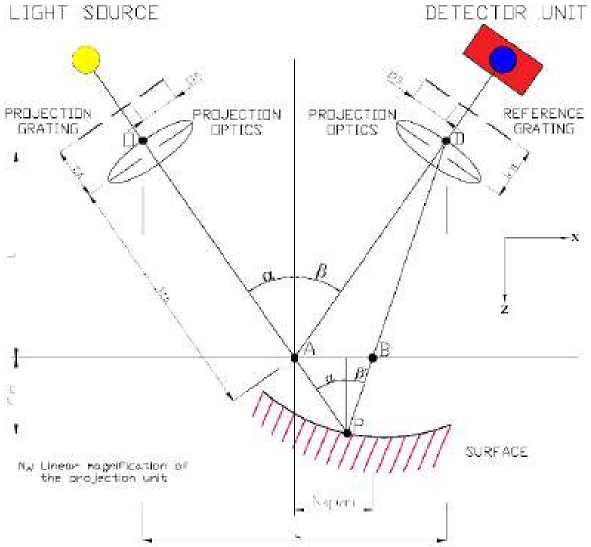


Figure 3
The base principle of projection moiré technique

(A)	Point where source light passes through the reference plane
(B)	Point where reflected source light passes through the reference plane
(D)	Projection optics on the detector's side
(h_n)	Depth of n_{th}-order moiré pattern measured from the reference plane
(k_A)	Distance between A and projection optics on the illumination's side
(k_B)	Distance between the reference grating and optics on the detector's side
(l)	Distance of projection and reference grating measured from the reference plane
(n)	Order of the moiré pattern
(N_A)	Linear magnification of the projection unit
(O)	Projection optics
(P)	Measured point
(p_A)	Pitch of projection grating

(p_B)	Pitch of reference grating
(s)	Distance between the projection optics O and D
(t_A)	Distance between the projection grating and optics on the illumination's side
(α)	Incidence angle (of incoming light)
(β)	Viewing angle at A
(β')	Viewing angle at P

2 Materials and Methods

The segmenting algorithm was developed in MATLAB® version 9.5.0.944444 (R2018b) [15] based on exploratory sequences and observations performed on 11 MIs made available by SALUS Ortopédtechnika Kft. Original MIs were software-generated applying digital PMT, and have a resolution of 2448 x 3264 px in 10 cases and 2736 x 3648 px in 1 single case with a bit depth of 24 and DPI of 96. MIs show patients in standing position facing the reference wall, and non-ROI areas that typically contain irrelevant image content of residual grating and non-moiré parts outside the back region. The procedure of image processing involves two main phases: (1) preprocessing MIs, (2) segmenting MFs using a sequence of filtering and morphological operations. Based on operation parameters applied in phase (2), two MI groups (G1, G2) are distinguished. For MIs in G1, identical parameters of processing phases result the similar outcome. For G2, different parameters are required for similar results, even in the group itself (Table 1). The reason for this is to be found in different image characteristics in terms of contrast, noise and moiré blur/confluence that are likely to result from dissimilar measurement setups. The phases of the code are illustrated in MI no. 2 of G1 (Fig. 4-14). For the other images, only the result of the segmentation is given in the overlap with grayscale ROIs (Fig. 15-20).

2.1 Preprocessing Moiré Images

In the first phase of image processing, original MIs are prepared for further processing by (a) manual selection of region of interests (ROIs) and (b) conversion into grayscale. As a result of these steps, input images for phase 2 are obtained. Selection of ROIs is performed by rectangular cropping using *imcrop* function. Original images are reduced in size based on selected ROI area with boundaries from the neck to the hip; and from the left upper arm to the right one (Fig. 4). Cropped images vary in size according to the size of specific ROI area and patient setup (distance from the camera). The resolutions of cropped images are between the range of 784x1044 px and 1136x1406 px.

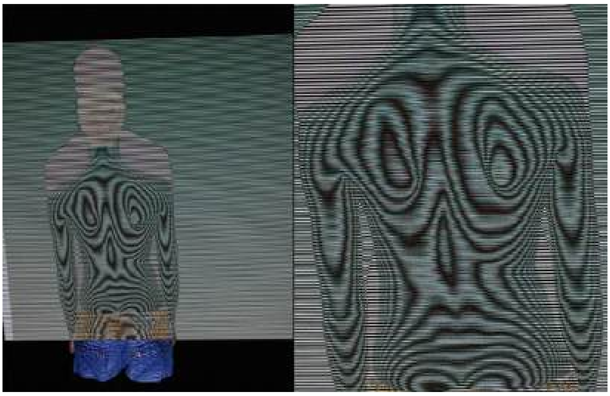


Figure 4
Original (L) and ROI-cropped (R) moiré image

Function *rgb2gray* is applied in order to convert cropped RGB images into grayscale (Fig. 5). For morphological operations discussed in phase (2), grayscale images contain all the relevant information of moiré stripes. Colour intensity values do not carry additional information here, and their conversion to grayscale does not induce data loss.

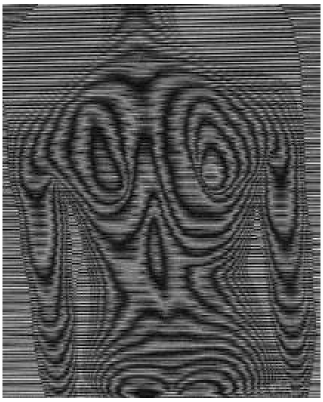


Figure 5
Grayscale moiré image with ROI

2.2 Steps of Moiré Fringe Segmentation

For segmenting MFs, a possible algorithmic approach is introduced. In the segmentation procedure, an empirically established sequence of filtering and morphological operations is used: (1) enhancing contrast, (2) increasing brightness, (3) refining contrast, applying (4) 2-D Gaussian filter and (5) dilation, (6) thresholding and (7) skeletonization.

Table 1

Summary of function parameters applied to moiré image (MI) groups G1 and G2

Phases	G1 (MI no. 1, 2, 3, 5, 6, 7, 9, 10)	G2 (MI no. 4, 8, 11)
Enhancing contrast [*imadjust by def.*]	3x	3x
Increasing brightness [increase in pixel value]	120	100 for MI no. 4 and 8 110 for MI no. 11
Refining contrast [range of intensity values]	[0.7 1]	[0.7 1]
2-D Gaussian filter [standard deviation]	6	6 for MI no. 4 and 11 8 for MI no. 8
Dilation [structuring element, pixel width, repetition]	square, 3, 3	square, 3, 3
Threshold value	0.41	0.35 for MI no. 4 and 11 0.38 for MI no. 8

2.2.1 Enhancing Contrast

For mapping the intensity values to new values and thereby enhancing contrast, *imadjust* function was applied in 2 steps. In the first step a slight contrast correction is performed via saturating the bottom 1% and the top 1% of all pixel values three times by the default operation of *imadjust* (Fig. 6).

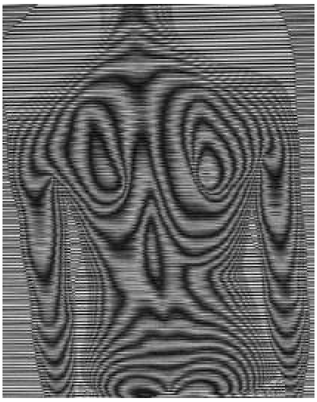


Figure 6

Result of contrast enhancement applied on grayscale moiré

2.2.2 Increasing Brightness

Before further contrast enhancement, brightness is increased by increasing pixel values of MIs of G1 by 120 and G2 by 100 and 110, respectively (Fig. 7).

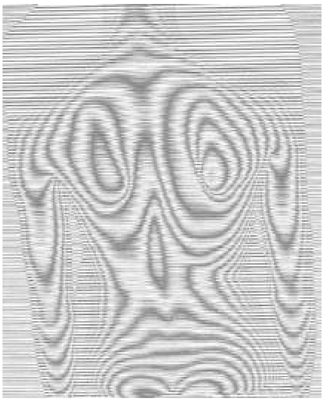


Figure 7
Result of brightness increase

2.2.3 Refining Contrast

As the second step in contrast adjustment, intensity values are mapped to new values between 0.7 and 1, by re-applying the function *imadjust*. The result is a stronger contrast of moiré stripes (Fig. 8).

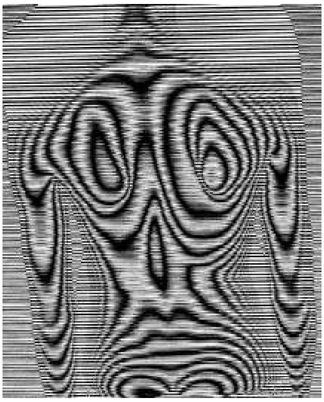


Figure 8
Result of contrast refinement

2.2.4 Applying 2-D Gaussian Filter

Image is filtered with a 2-D Gaussian smoothing kernel (*imgaussfilt*) with image specific standard deviation values 6 or 8 (Fig. 9).

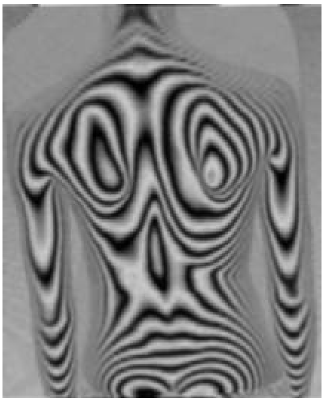


Figure 9
Result of 2-D Gaussian filtering

2.2.5 Applying Dilation

Blurred grayscale image is dilated by using *imdilate* and morphological structuring element *strel*. Dilation is applied three times in combination of square structuring element with a width of 3 pixels (Fig. 10). In Fig. 10, resulting differences from the previous step (2-D Gaussian filter) may not be obvious, however, dilation supports the results of thresholding and skeletonizing operations by gradually enlarging the boundaries of regions of foreground pixels.

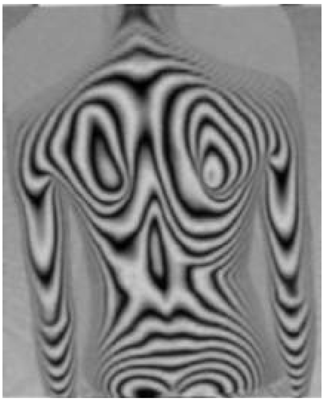
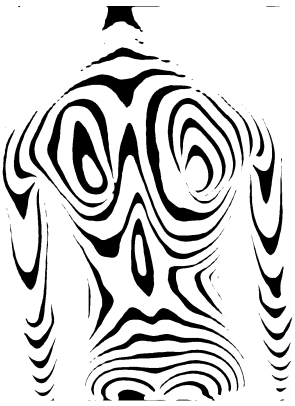


Figure 10
Result of dilation

2.2.6 Thresholding

Function *imbinarize* is used to convert the image to a binary image, based on a threshold value: all pixel values above a globally determined threshold are replaced with ones and all other values with zeros. The threshold value applied is covered in the range between 0.35 and 0.41 (Fig. 11).



Figurer 11
Result of thresholding

2.2.7 Skeletonization

Skeletonization was performed by using *bwmorph* function for morphological operations, specified as 'thin'. The operation 'thin' is applied for thinning binarized images to single lines, and repeated until the image no longer changes (i.e. parameter 'Inf' in the function input). The inputs of *bwmorph* are provided by complements of binarized images generated with the function *imcomplement*. For a better visualization of the results, lines of skeletonized images are fattened by applying the operation 'fatten' once. The result is shown enlarged as re-complemented image (Fig. 12) and as overlay on binarized (Fig. 13) and colour ROI images (Fig. 14).

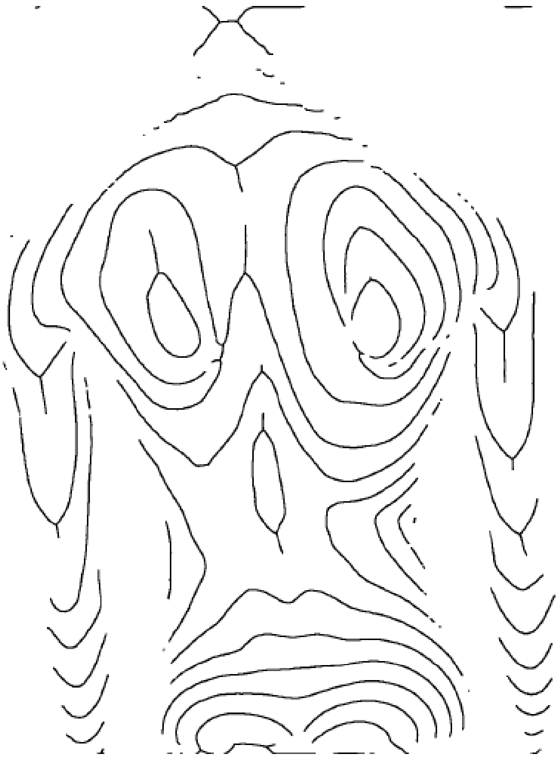


Figure 12
Result of skeletonization: segmented moiré fringes

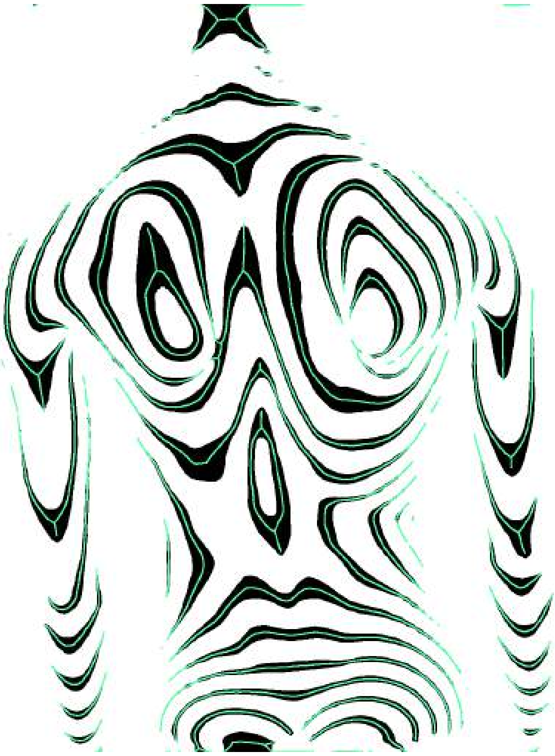


Figure 13
Overlay of segmented moiré fringes (green) on thresholded image (black)

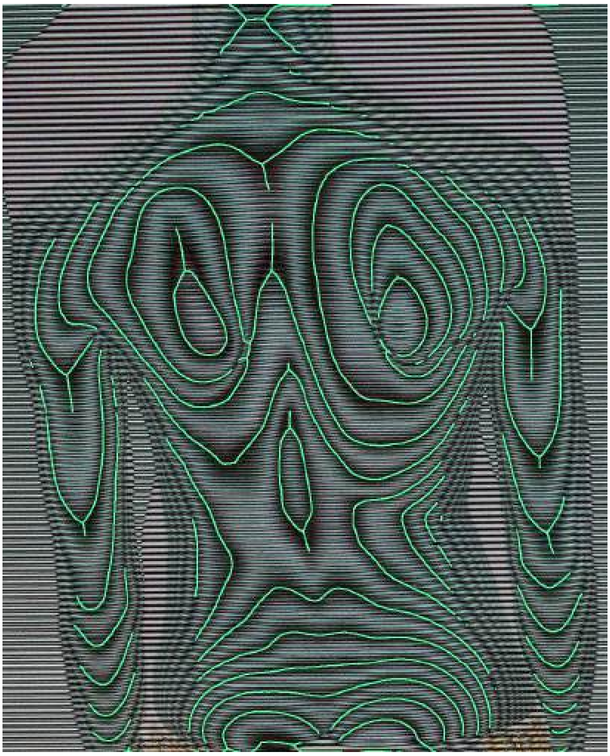


Figure 14
Overlay of segmented moiré fringes on colour ROI

3 Results and Discussion

Results show that the segmenting method is simple, fast to process and, for the most part of the image, follows the moiré stripes accurately (Fig 15-20). The average processing time of the algorithm from grayscale conversion to skeletonization is 0.146 s per image. In Table 2, the time course of the algorithm, with exclusion of manual ROI selection, is summarized in average elapsed and processing time.

The segmenting algorithm leads to a partial or sporadic segmentation of moiré stripes. Image details (i.e. parts of moiré stripes) and 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. 21). In terms of general usability of the code, the necessity of re-adjusting static function parameters is challenging and–especially in higher patient populations–time consuming. To get similar results on MIs other than the 11 sample images applied in this study, function parameters need to be empirically determined and implemented in the code. Therefore, static function parameters are desired to be eliminated with automatic adaptive and dynamic parameterization. Also, for problems (a-e), a more sensible solution is required. A possible way for further research might be to improve the algorithm with (1) adaptive and dynamic function parameters based on values of low contrasted and over contrasted images in combination with adaptive thresholds, (2) applying high-pass filters for image sharpening. Another possible direction of research is (3) to combine the algorithm with segmentation approaches based on a fuzzy inference system [16]. Due to its simplicity and fast operation, an improved solution of the algorithm could also replace time demanding and complex segmentation methods.

Table 2

Time course of the segmenting algorithm

Proc. Nr.	**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), RAM: 8 GB

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

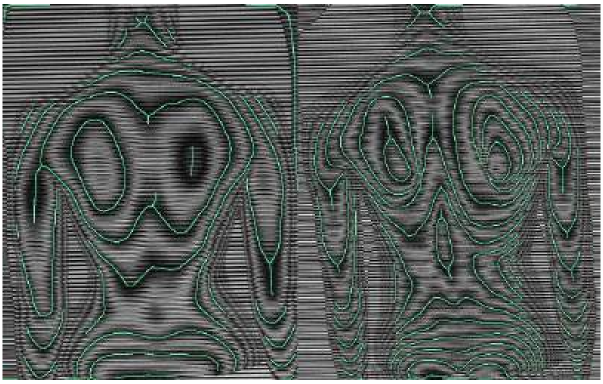


Figure 15
Segmented moiré fringes of image no. 1 (L) and 2 (R)

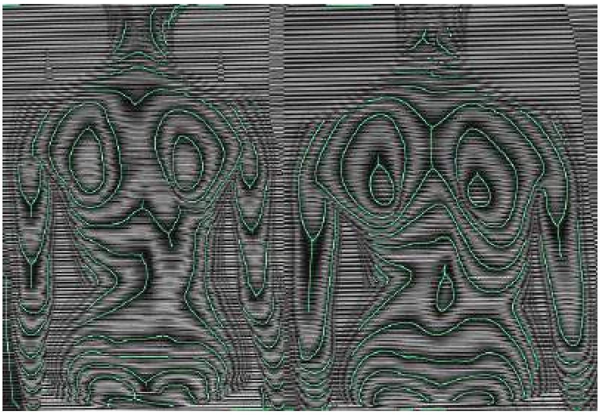


Figure 16
Segmented moiré fringes of image no. 3 (L) and 10 (R)

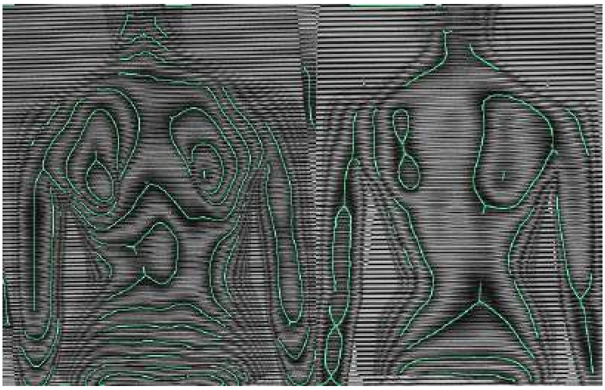


Figure 17
Segmented moiré fringes of image no. 5 (L) and 6 (R)

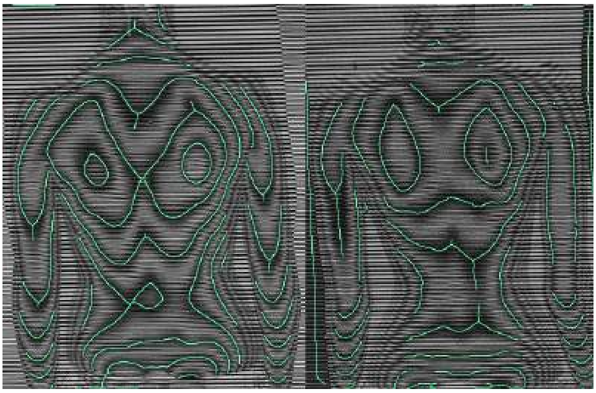


Figure 18
Segmented moiré fringes of image no. 7 (L) and 9 (R)

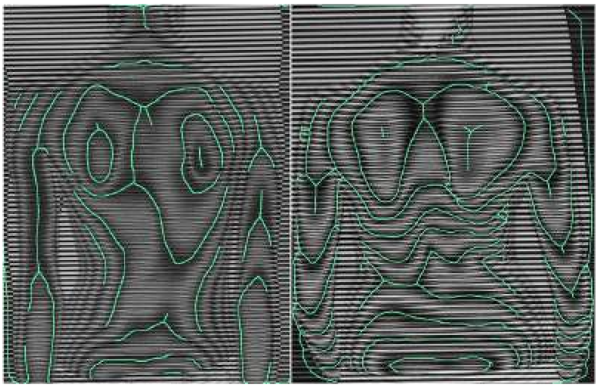


Figure 19
Segmented moiré fringes of image no. 4 (L) and 8 (R)

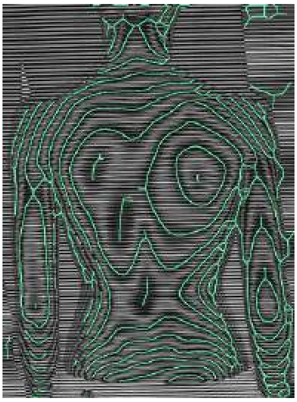


Figure 20
Segmented moiré fringes of image no. 11

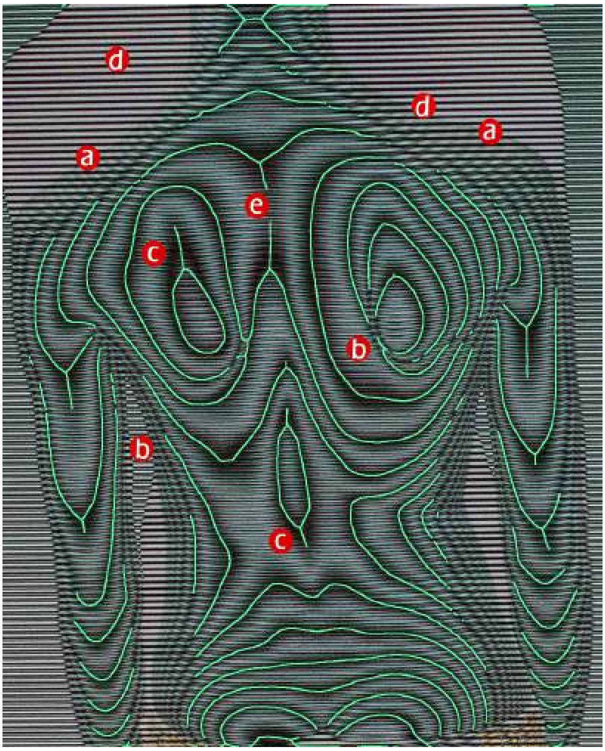


Figure 21
Problems to be handled in moiré fringe segmenting algorithm
(a-c) pale, convergent, and wider/blurred moiré fringes
(d) noise of residual grating
(e) unwanted branches

Conclusion

In this study, an initial phase of research on MF segmentation of scoliotic spines is conducted, presenting an algorithmic sequence of filtering and morphological operations with static function parameters in MATLAB® environment. 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 indicate that the algorithm introduced 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.

Acknowledgment

We would like to express our gratitude to Salus Orthopedtechnika Kft. (István Joó, Katalin Prommer, Ferenc Marlok) for providing us sample images and granting permission to our study.

References

[1] J. W. S. Rayleigh. On the manufacture and theory of diffraction gratings. *Philosophical Magazine,* 47:81-93, 1874

[2] H. Takasaki. Moiré topography. *Applied Optics*, 9(6):1467-72, 1970

[3] H. Takasaki. Moiré topography. *Applied Optics*, 12(4):845-52, 1973

[4] Takei T., Yokosawa S., Innami T., Miyazawa T., Kuwana T., Takagi M., Furukawa A. Application of Moiré Topography to Forensic Odontology. The Journal of Nihon University School of Dentistry, Vol. 27(2), 1985, 87-104

[5] Wood, J. D.; Wang, R.; Weiner, S.; Pashley, D. H. Mapping of tooth deformation caused by moisture change using moiré interferometry. Dent. Mater, Vol. 19(3), 2003, 159-166

[6] Jelen K., Kusová S. Pregnant women: Moiré contourgraph and it's semiautomatic and automatic evaluation. Dedicated to Professor Antonín Dolezal on his 75th birthday anniversary. Neuro endocrinology letters, Vol. 25, 2004, 52-56

[7] Á. Antal. Optikai úton generált Moiréfelületek hibaanalízise és identifikálása méréstechnikai alkalmazásokkal [dissertation on the internet]. Budapest, Hungary, University of Technology and Economics, 2009 [cited 2021 February 24] Available from: https://repozitorium.omikk.bme.hu/bitstream/handle/10890/851/ertekezes.pdf?sequence=1&isAllowed=y

[8] F. Porto, J. L. Gurgel, T. Russomano, P. T. V. Farinatti. Moiré Topography: From Takasaki Till Present Day. In Grivas T. B., Editor: *Recent advances in scoliosis*, pp. 103-118, 2012

[9] M. Batouche, R. Benlamri. A computer vision system for diagnosing scoliosis. In *Proceedings of IEEE International Conference on Systems, Man and Cybernetics*, 3, pp. 2623-2628, 1994

[10] H. S. Kim, S. Ishikawa, Y. Ohtsuka, H. Shimizu, T. Shinomiya, M. A. Viergever. Automatic scoliosis detection based on local centroids evaluation on Moiré topographic images of human backs. *IEEE Trans Med Imaging*, 20(12):1314-1320, 2001

[11] T. Ikeda, H. Terada. Development of the moiré method with special reference to its application to biostereometrics. *Opt. Laser Technol*, 12:302-306, 1981

[12] H. Kim, H. Ushijima, S. Ishikawa, Y. Otsuka, H. Shimizu, T. Shinomiya, M. A. Viergever. Scoliosis detection based on difference of apexes position and angle on Moiré topographic images. *International Congress Series*, 1268:1294, 2004

[13] P. Balla, G. Manhertz, Á. Antal. Diagnostic moiré image evaluation in spinal deformities. *Optica Applicata*, 46:375-385, 2016

[14] H. Zhi, R. B. Johansson. Interpretation and classification of fringe patterns. *Optics and Lasers in Engineering*, 17(1):9-25, 1992

[15] MATLAB (2018) 9.5.0.944444 (R2018b). Natick, Massachusetts: The MathWorks Inc.

[16] H. W. Wing, Y. S. Kin. Moiré Fringe Segmentation Using Fuzzy Inference System. In: H. Ibrahim, S. Iqbal, S. S. Teoh, M. T. Mustaffa, Editors: *9th International Conference on Robotic, Vision, Signal Processing and Power Applications.* Lecture Notes in Electrical Engineering, 398. Springer, Singapore, 2017

Biomechanica Hungarica 2022;15(2):7-21

SCOLIOTICUS GERINC MOIRÉFELVÉTELEINEK SZOFTVERES SZEGMENTÁCIÓJA

Bogdán Csaba[1*], Magony Andor Dániel[2], Hargitai Evelin Gabriella[2], Antal Ákos[3], Tunyogi-Csapó Miklós[4]

[1] Pécsi Tudományegyetem, Általános Orvostudományi Kar, Klinikai Orvostudományok Doktori Iskola

[2] Pécsi Tudományegyetem, Általános Orvostudományi Kar, Transzdiszciplináris Kutatások Intézete

[3] Budapesti Műszaki és Gazdaságtudományi Egyetem, Mechatronika, Gépészmérnöki Kar, Optika és Gépészeti Informatika Tanszék

[4] Országos Gerincgyógyászati Központ, Budai Egészségközpont

DOI: 10.17489/biohun/2022/2/558

Absztrakt

A scolioticus gerinc vizsgálatára a röntgenfelvételek részleges alternatíváját nyújtja a hátfelszín moiréfelvételeinek elemzése. A *scoliosis* moiréjelenségen alapuló diagnosztikájában a moiréfelvételek általánosan megbízható, gyors és precíz szegmentációja szignifikáns szerepet tölt be, és még kidolgozásra vár. Ez a kutatás a moiréfelvételek szegmentációjára kíván megoldási javaslatot tenni digitális (projekciós) moirétechnika és XOR-logika alkalmazásával létrehozott moiréfelvételek manuális/félautomatikus szegmentációjára kifejlesztett szoftveralapú megoldással, a *Moiré Fringe Segmentation Tool* prototípusával. A prototípus MATLAB App Designer alkalmazásban készült, és képszűrési és morfológiai műveletekkel biztosítja a moirésávok szegmentációját (1) fényerő- és (2) kontrasztjavítás, (3) 2-D Gauss-féle elmosás, (4) küszöbölés, (5) hisztogram kiegyenlítés, (6) inverzió, valamint a (7) szkeletonizáció implementálásával. A szoftver a moirésávok szegmentációját kvázi valós időben, manuálisan állítható szűrési és morfológiai képfeldolgozási műveletekkel, valamint előre meghatározott szekvencián alapuló, beépített algoritmussal támogatja. A prototípus alkalmazhatóságát egyszerű, gyors és a felvételek moirésávjainak nagy részét pontosan lekövető szegmentálás igazolja. Az eredmények azt mutatják, hogy a prototípus koncepciója megfelelő alapot nyújt a moirésávok szegmentációjához és további, kiterjesztett képfeldolgozási műveletekkel operáló kutatás-fejlesztéshez. Egyszerűségének és gyors működésének következtében a prototípus továbbfejlesztett megoldása helyettesítheti az időigényes és komplex szegmentálási módszereket is.

Kulcsszavak: moire topográfia, moiremintázat, számítógéppel segített képfeldolgozás, szoftver, *scoliosis*

***Levelező szerző elérhetősége:** H-7624 Pécs, Szigeti u. 12., Doktori (PhD) és Habilitációs Iroda
E-mail: *csaba.bogdan@pte.hu* **Tel.:** +36 30 422-8704

Citáció: *Bogdán C, Magony AD, Hargitai EG, Antal Á, Tunyogi-Csapó M. Scolioticus gerinc moiréfelvételeinek szoftveres szegmentációja. Biomech Hung 2022; 15(2):7-21.*

Beérkezés ideje: 2022.11.03. **Elfogadás ideje:** 2022.12.07.

SOFTWARE-BASED SEGMENTATION OF MOIRÉ IMAGES OF SCOLIOTIC SPINE

Abstract

The analysis of moiré images of the human back provides a partial alternative to radiographs at examining the scoliotic spine. In moiré-based diagnosis of scoliosis, the generally reliable, fast and precise segmentation of moiré images plays a significant role, and is still waiting to be developed. For the segmentation of moiré images produced by (digital) projection moiré and XOR logic, this study aims to propose a software-based solution, the Moiré Fringe Segmentation Tool developed for manual/semi-automated detection of moiré fringes. The prototype was produced in MATLAB App Designer and performs the segmentation of moiré fringes by implementing image filtering and morphological operations for (1) brightness and (2) contrast enhancement, (3) 2-D Gaussian filter, (4) thresholding, (5) skeletonization, (6) histogram equalization and (7) inversion. The software allows the segmentation of moiré fringes in quasi-real-time, by manually adjustable filtering and morphological operations and a built-in algorithm of predefined image processing sequence. The applicability of the prototype is proven by a simple, fast to process and, for the most part of the sample images, accurate segmentation in quasi-real-time. The results show that the concept of the prototype provides a suitable base for the segmentation of moiré fringes and further research and development aiming to extend image processing operations. Due to its simplicity and fast operation, an improved solution of the prototype can replace time-consuming and complex segmentation methods.

Keywords: moire topography, moire patterns, computer-assisted image processing, software, scoliosis

BEVEZETÉS

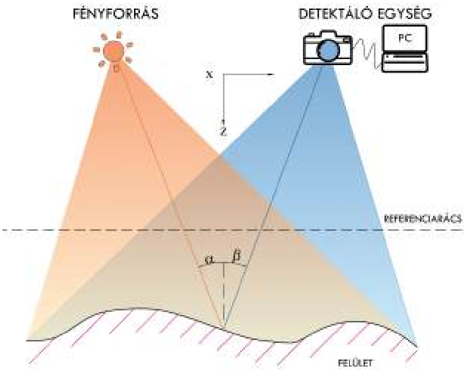
A különböző gerincdeformitások diagnosztikája már régóta foglalkoztatja az orvostudományt. A gyermekek és serdülők posturalis elváltozásai fontos egészségügyi és társadalmi kockázatokat hordoznak, gyakori megjelenésük és progressziójuk pedig a kutatások nyugtalanító következtetései.[1-5] A gerinc kóros elváltozásai kezdetben aszimptomatikusan alakulnak ki, és hatásuk az élet későbbi éveiben érezhető. A kiváltott fájdalom, az osteoarticularis rendszer súlyos deformációi és belső szervi rendellenességek jelentősen ronthatják az életminőséget.[1,6,7] Következésképpen a gerincdeformitás progressziójának prevenciójában a szűrés tekinthető a legfontosabb tényezőnek, amely során a testtartás megfelelő diagnosztikája objektív módszereket igényel. Napjainkban a gerincelváltozások diagnosztikájának aranystandardja a radiográfiai (röntgen) vizsgálat.[8-10] Fokozott szenzitivitásuk következtében, a radiográfiai vizsgálatokból eredő nem kívánatos, akár a genetikai anyag módosulásához vezető sugárzási hatásoknak leginkább a gyermekek és serdülők vannak kitéve.[1,11-13]

A röntgen-képalkotás hátrányai, mint az ionizáló sugárzás, az idő- és ismétlésigény, a szükséges eszközi és környezeti feltételek, valamint a felmerülő költségek olyan módszertani kutatásokat indokolnak, amelyek lehetővé teszik a gerinc elváltozásainak gyors, költséghatékony és káros sugaraktól mentes diagnosztikáját. A scolioticus gerinc szűrésére számos nem-ionizáló és non-invazív módszert javasoltak,[1] köztük a moiré topográfiát (MT), a (video-) raszteres sztereográfiát (Diers Formetric),[14,15] a 3-D ultrahangos képalkotást (Scolioscan)[16,17] és az infravörös termográfiát (IR termográfia).[18]

1970-ben a MT-t mint a klinikai diagnosztikában alkalmazott topográfiai vizsgálatok egyik első technikáját emberi testfelületek vizsgálatára javasolták.[19] A MT a moiré jelenségén alapul, amely akkor jön létre, ha két hasonló, ismétlődő mintázatból álló geometriai struktúra tökéletlen középpont-középpont beállítással egymással átfedésbe kerül. Ekkor egy világos és sötét vonalakból álló eredő csíkozat, a moiréjelenség figyelhető meg (*1. ábra*). Általánosságban a sötét sávokat nevezzük moirécsíkoknak vagy moirésávoknak (MS). Az alapstruktúrák (vagy rácsok) egymásra hatásának eredményeként megjelenő moiréjelenség méréstechnikai alkalmazásának alapgondolata az, hogy ha a rácsok közül az egyik a vizsgálandó felület egy adott állapotával van kapcsolatban, míg a másik egy ettől eltérő állapottal, – amely akár egy referencia állapot is lehet – az eredő mintázatokból következtethetünk a két állapot – adott esetben az egyik állapot és a referencia – közötti eltérésre. Másképpen fogalmazva: az eredő jelenségből visszafejthető a felület egy adott állapota a másik – vagy a referencia – ismeretében.[20]

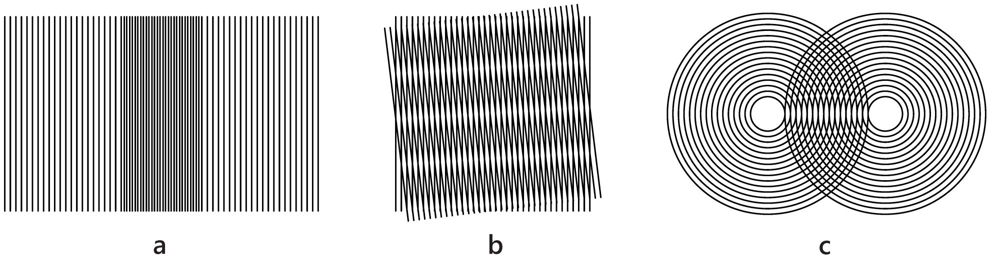
A moiréjelenség létrehozása technikafüggő, és akár olyan rácsokból is előállítható, amelyek nem tényleges fizikai objektumok. Ilyen technikát valósítanak meg az ún. árnyék- és projekciósmoiré-berendezések. Árnyékmoiré-technika (*2. ábra*) esetén a fizikai rács vizsgálandó felületre vetített árnyéka járul hozzá az interferenciához, és ezáltal a moirécsíkok megjelenéséhez szükséges második rácsként.

Projekciós MT alkalmazásakor a tárgy felületére szintén csak egy alaprácsot vetítünk, ám itt szoftveres képfeldolgozás útján hozzáadott virtuális ráccsal hozzuk létre a moiréjelenséget (*3. ábra*). A projekciósmoiré-berendezéshez csupán egy digitális fényképezőgép, egy számítógép, valamint egy (digitális vagy videó-) projektor szükséges. A *4. ábra* az emberi gerinc digitális (projekciós) technikával létrehozott moirémintázatát mutatja, amely a hátfelület egyedi karakterisztikáját jellemezve további diagnosztikai célzatú elemzésekre alkalmazható.



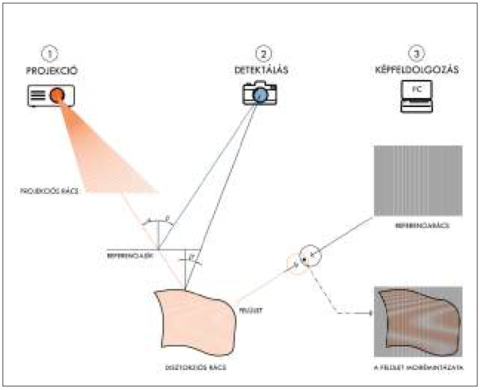
2. ábra. Az árnyékmoiré-technika sematikus ábrája

Magyarországon az 1980-as években Gréczy és mtsai[21] a *scoliosis* szűrésére irányuló vizsgálataikra alapozva konkludálták, hogy a moirétechnika és az Adams-teszt együttes alkalmazása megfelel a modern szűrővizsgálat követelményeinek, valamint megoldást kínál a *scoliosis* tömeges szűrésére. Javasolták továbbá

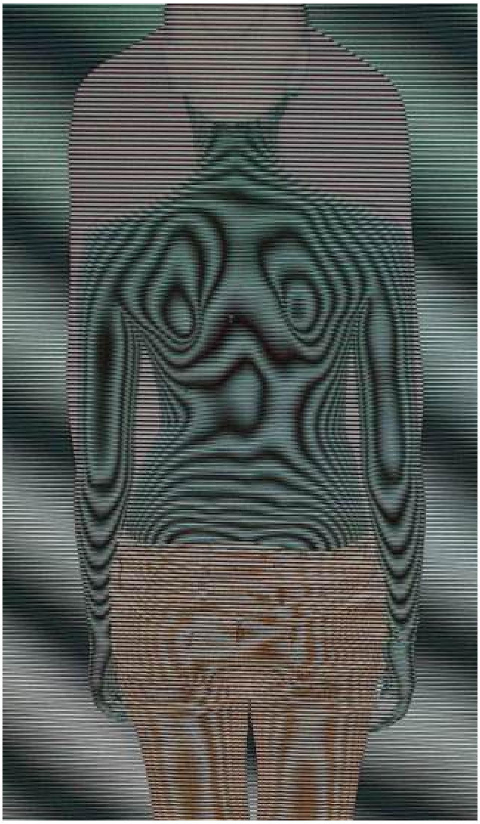


1. ábra. Azonos *(a)* és *(c)*, valamint eltérő szögű azonos *(b)* geometriájú struktúrák moirémintázatai a MT iskolaorvosi szűrővizsgálat-rendszerbe való beépítését és moirékészülékek az ország vezető és megyei ortopéd szakintézeteibe történő telepítését, mivel úgy találták, a MT és a hagyományos radiográfiai vizsgálat egymást hasznosan kiegészítő módszerek, és együttes használatuk lehetővé teszi a *scoliosis rotatios* és *frontalis* síkú komponensének feltérképezését. Az előzőekhez hasonlóan további hazai és nemzetközi kutatások is kiemelik, hogy mivel a MT segítségével a hát *frontalis* és *saggitalis* síkban vett elváltozásai kimutathatók, a technika ortopédiai szűrésekre és diagnosztizálásra egyaránt felhasználható.[22-25] Az egykori Egészségügyi Minisztérium 2008-as szakmai protokollja a *scoliosis* fizioterápiájáról a diagnosztikai és képalkotó vizsgálatok között a kétirányú, álló helyzetben készült röntgenfelvétel és spirometriás / spiroergometriás vizsgálatok mellett a MT lehetőség szerinti használatát ajánlotta.[26]

Az MT szignifikáns előnye, hogy nem-invazív, káros sugaraktól mentes, tetszőleges ismétlésszámú, gyors, valamint tömegméretekben alkalmazható költséghatékony mérést tesz lehetővé könnyen mobilizálható eszközökkel. A gerinc görbületi szögének számításához megfelelően kiválasztott és algoritmizált moirétechnika alkalmas lehet a röntgenfelvételek helyettesítésére vagy kiegészítésére *scoliosisban*.[1,27-29] Ugyanakkor komoly korlátot jelent, hogy a felülettopográfiai vizsgálatok *scoliosisban* történő alkalmazásakor általánosan megbízható eredményekhez vezető metodológiai standard nem került kidolgozásra.[30] Így komoly hátránya a MT-nak, hogy bár a felület alakjára vonatkozó információt megadja, nem feltétlenül vonhatók le egyértelmű következtetések. A moiréfelvételek feldolgozásához (sávszegmentáció és –elemzés) és kiértékeléshez szükséges munkaintenzitás ugyancsak jelentős, ennek legjobb megoldását – különösen nagy betegpopulációt felölelő, rövid időn belül végrehajtandó vizsgálatok esetén – egy automatikus rendszerben látják.[31-36]



3. ábra. A projekciósmoiré-technika sematikus ábrája



4. ábra. Az emberi hátról készített digitális (projekciós) moiréfelvétel

A moiréfelvételek feldolgozása számos egyedi megoldást igényel, amelyre kihat az optikai elrendezés (ti. a referenciaterület, a páciens, a fényforrás/projektor és a detektor egymáshoz viszonyított távolsága és térbeli pozicionálása), az alkalmazott megvilágításból adódó intenzitáseloszlás (intensity distribution), valamint a zaj és a detektálás jellege. Ennélfogva, egy teljesen automatizált moiréképanalízis megvalósítása jelentős kihívást jelent, ugyanakkor kívánatos célt is a területen.[20,37,38] A moirémintázat-analízis bizonytalansági faktorainak csökkentésében a MS-ok precíz szegmentációja alapvető jelentőséggel bír.[39]

Megjegyzendő, hogy a gerinc moiréfelvételeinek hatékonyabb elemzése még további kutatásokat igényel, amelyben a mérnökök és orvosok elszánt és érdemi összefogása, a műszaki-orvosbiológiai tudás összehangolt alkalmazása alapvető szerepet játszik. Ennek a multi- és interdiszciplináris tudásnak az összehangolása e tanulmánynak is a központi törekvése.

CÉLKITŰZÉSEK

A moirémintázatok szegmentációs kihívásaira adott válasz gyanánt egy szoftver alapú MS-szegmentáló alkalmazás, angol munkacímén *Moiré Fringe Segmentation Tool* (MFST) koncepciója és prototípusa került kifejlesztésre. Az MFST célja, hogy segítse a MS-ok detektálását és kontúrozását kvázi valós időben (*quasi-real-time*, QRT), manuálisan állítható képfeldolgozási műveletek és előre meghatározott szekvenciákon alapuló félautomata algoritmusok alkalmazásával. A koncepció lényege, hogy ösztönzi az orvosi és orvosbiológiai szakemberek gyakorlati és felfedező jellegű moirékutatásait *scoliosisban*, oly módon, hogy reális és megvalósítható választ ad a manuális és automatizált MS-szegmentáció képfeldolgozási problémáira. A javasolt szoftver alapú prototípus célja, hogy moiréfelvételek gyors és precíz szegmentációja által bemenetet biztosítson a MS-ok és azok matematikai-geometriai összefüggéseinek elemzéséhez gerincgörbületi szögértékek számítására alkalmazható módszerek feltárása érdekében. Fontos kiemelni, hogy az alkalmazás használatával nyerhető szegmentált moiréfelvételek további, diagnosztikai célzatú kiértékelése e kutatás későbbi fázisaiban, külön szoftverben valósul meg.

ANYAG ÉS MÓDSZER

A MS-ok detektálására a szoftver működési elve egy manuális/félautomata megoldást követ. A szoftver jellemzőit és kulcsfontosságú funkcióit egy MS-szegmentáló algoritmus kifejlesztésére irányuló előzetes kutatás megfigyelései és következtetései[40] határozták meg. Ennek során 11 db, XOR (kizáró vagy) logikával létrehozott (digitális) projekciós moiréfelvételen képszűrési és morfológiai műveleteket alkalmazó képfeldolgozási szekvencia került bemutatásra. Az MFST logikai elrendezése és felépítése az előzetes kutatásban ajánlott algoritmus dilatáción kívül eső képfeldolgozási lépései alapján került kialakításra. A felhasználói felület és a szoftver felépítése egyaránt követ funkcionális és kényelmi szempontokat, figyelembe véve WIKLUND felhasználóbarát orvosi interfészek tervezéséhez javasolt megoldásait.[41] Az MFST kódja és grafikus felhasználói felülete a MATLAB App Designer (R2018B) programrendszerben[42] került kifejlesztésre.

A felhasználói felület kidolgozása során elsődleges szempont volt a felhasználók által potenciálisan használt szoftverek vizuális elemeihez való igazodás. Ennek érdekében a gombok a legismertebb képszerkesztő és -feldolgozó szoftverek dizájnját követik (pl. Photoshop, GNU Image Manipulation Program [GIMP]), és a felhasználó számára megnyíló ablakok elrendezése is a megszokott irodai grafikus szoftverek arculatához illeszkedik.

Az MFST felhasználói felületének kulcselemei a következők: (1) képfeldolgozási műveletek mezője, (2) beépített algoritmusok gombsora, (3) a képfeldolgozás fázisainak előnézeti panelje és (4) a standard műveleteket előhívó gombok (*5. ábra*).

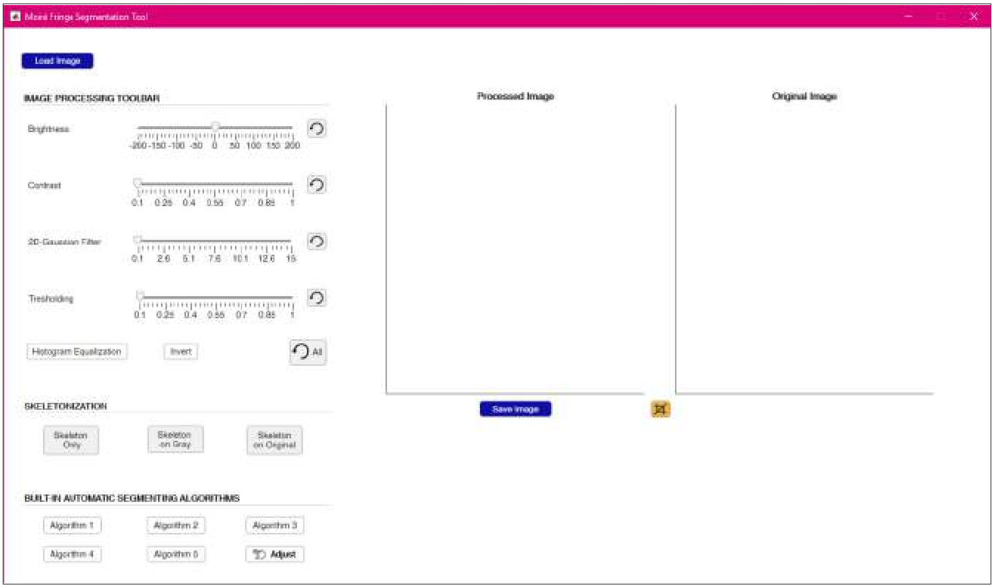
A (1) képfeldolgozási műveletek mezője szűrési és morfológiai képmanipulációs funkcióival a QRT-képfeldolgozáshoz igazított címkéket és beállításokat tartalmazza. A szűrési és morfológiai funkciók által valósul meg a fényerő, a kontraszt, a küszöbölés, a 2-D Gauss-féle elmosás és a szkeletonizáció manuális paraméterezhetősége.

A (2) beépített algoritmusok célja, hogy támogassák a manuális MS-detektálást azáltal, hogy előre meghatározott, automatizált morfológiai képfeldolgozást biztosítanak. Az automatikus algoritmusok körét a legkülönfélébb forrásokból származó moiréfelvételekre adaptált szegmentációs módszerek tanulmányozásával kívánjuk bővíteni. Jelen tanulmány a prototípusba az automatizált MS-detekció szemléltetésére az előzetes kutatásban alkalmazott statikus megoldást építette be.

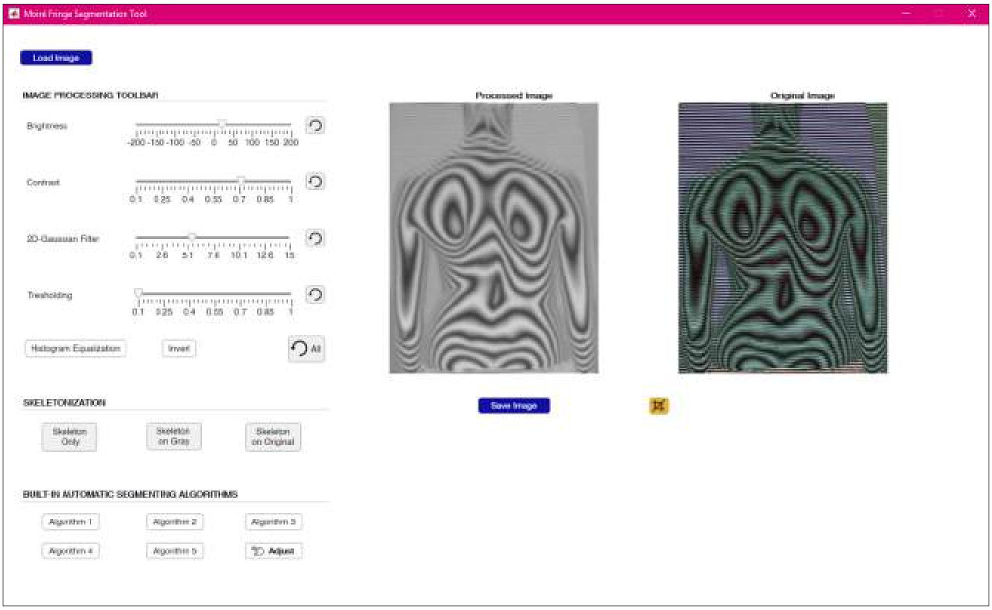
Az (3) előnézeti panel a képfeldolgozási eredmények QRT vizualizációjaként szolgál. A (4) standard műveleteket előhívó gombok célja pedig alapvető feladatok végrehajtása, mint például a moiréfelvételek programba töltése, a szerkesztett képek exportálása és beállítások visszaállítása (reset funkció).

EREDMÉNYEK

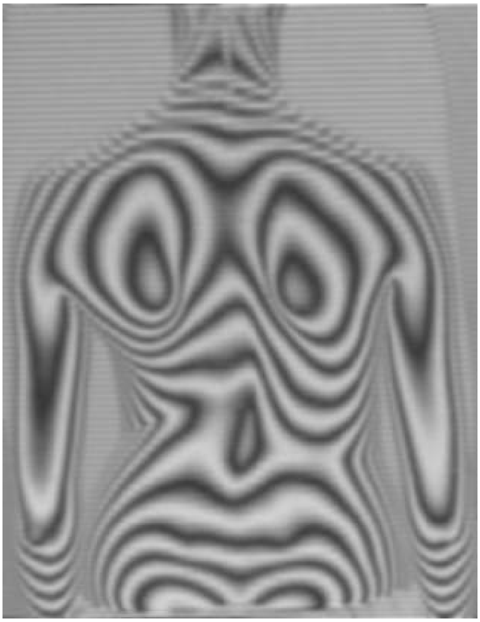
Az MFST prototípusa lehetővé teszi az XOR logikával létrehozott moiréfelvételek dinamikusan változtatható és felhasználóbarát szegmentációs célzatú képfeldolgozási konfigurációit. Az alkalmazás által támogatott QRT szegmentálási módszer egyszerű, gyors és a képek moirécsíkjainak nagy részét pontosan leköveti. A prototípus grafikus felhasználói felülete (*5. ábra*) négy fő területre tagolódik: (1)



5. ábra. A *Moiré Fringe Segmenting Tool* prototípusának főképernyője



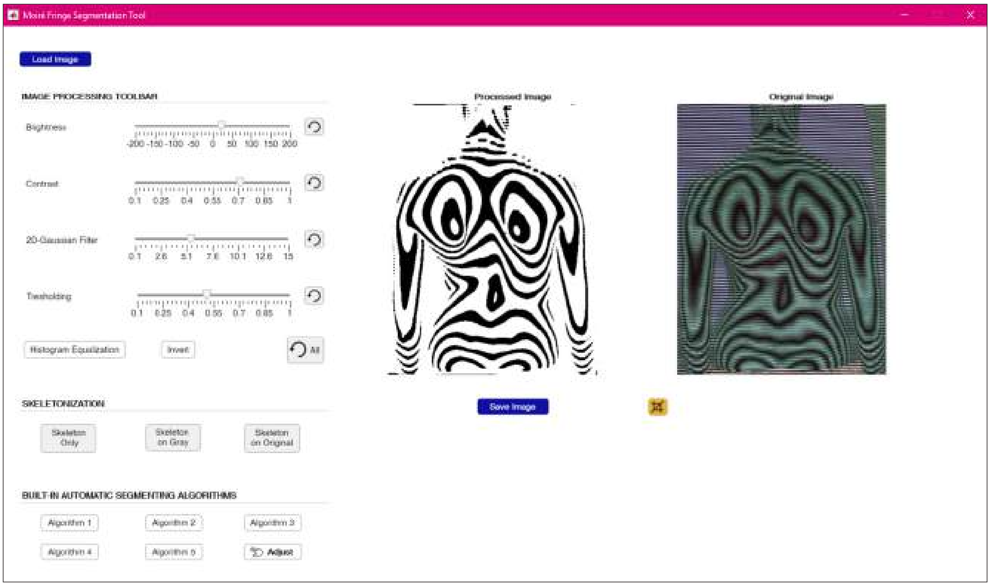
6. ábra. A *Moiré Fringe Segmentation Tool* prototípusában végrehajtott fényerő- és kontrasztjavítás, valamint a 2-D Gauss-féle elmosás eredménye



7. ábra. A *Moiré Fringe Segmentation Tool* prototípusában végrehajtott fényerő- és kontrasztjavítás, valamint a 2-D Gauss-féle elmosás eredménye nagyítva

a képvászonra, amely az eredeti (referencia) és az éppen feldolgozott képet jeleníti meg, (2) a képfeldolgozó eszköztárra, (3) a szkeletonizált eredmények megjelenítésére szolgáló eszköztárra, valamint (4) a beépített, automatikus szegmentációt kiszolgáló algoritmusokra.

A manuális szegmentálási eljárás fő fázisait a *6-11. ábra* szemlélteti. Az *„Algorithm 1”* gombbal végzett automatizált szegmentálás eredményét a *12. ábra* mutatja. A szoftver működésének folyamatát pedig a *13. ábra* szemlélteti. Bár a prototípusban használt megoldás viszonylag szűk képszűrési és képfeldolgozási műveleteket alkalmaz, mégis lehetővé tesz vizuálisan követhető és viszonylag pontos, akár diagnosztikához használható MS-delineációt. Egyszerűségének és gyors működésének következtében az MFST továbbfejlesztett, képfeldolgozási funkcióira nézve kibővített megoldása pedig helyettesítheti az időigényes és komplex szegmentálási módszereket is. Az automatikus algoritmusok végrehajtási sebessége a képfelbontástól és az alkalmazott



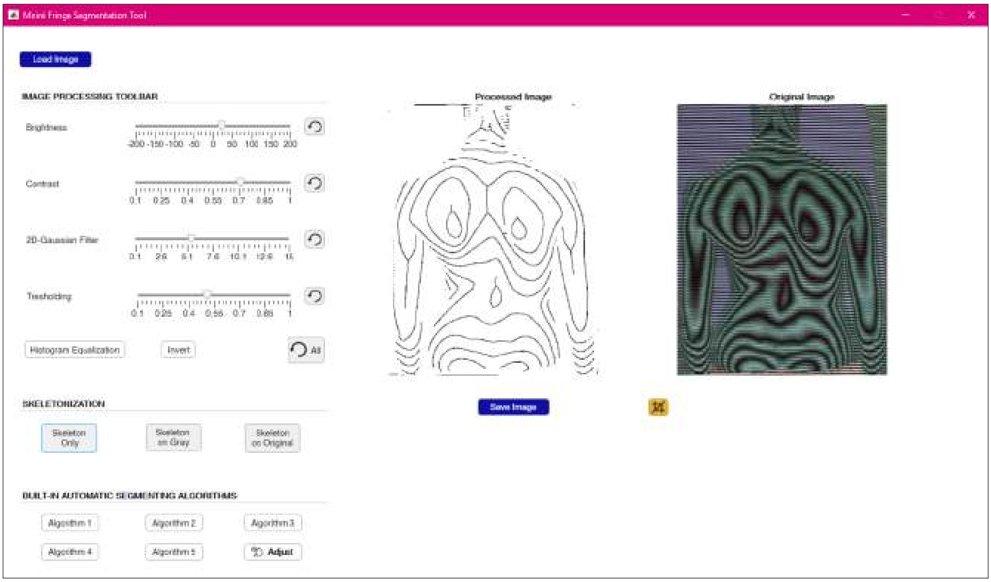
8. ábra. A *Moiré Fringe Segmentation Tool* prototípusában végrehajtott küszöbölés (thresholding) eredménye

szegmentációs metódus összetettségétől és optimalizáltságától függ. Az illusztrációhoz felhasznált moiréfelvétel felbontása 1008 x 1304 px, amit a statikus paramétereket alkalmazó automatikus algoritmus mintegy egy másodpercen belül dolgoz fel. A képfeldolgozás alsó középkategóriás Windows 10 PC-rendszer konfigurációján került végrehajtásra (CPU: Intel® Core™ i5-8300H @ 2.30 GHz, GPU: NVIDIA GeForce GTX 1050 4 GB, RAM: 8 GB).

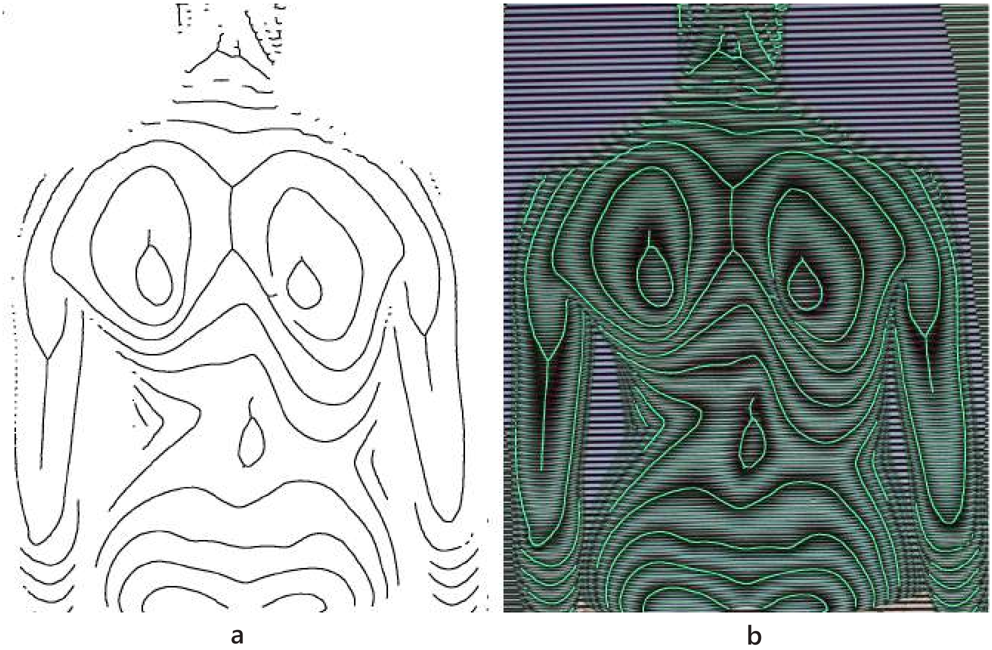
9. ábra. A *Moiré Fringe Segmentation Tool* prototípusában végrehajtott küszöbölés (thresholging) eredménye nagyítva

Képvásznak

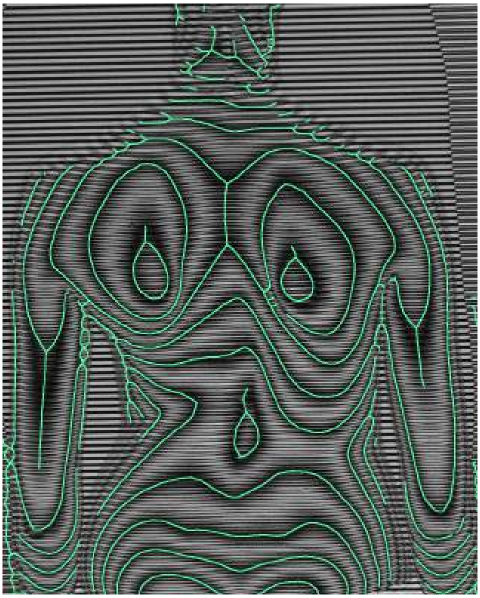
Az MFST grafikus felhasználói felületének jobb oldalán két képvászon található: az egyik az eredeti kép, amely referenciaként szolgál („*Original Image*”), a másik pedig a QRT-képfeldolgozás eredményét jeleníti meg („*Processed Image*”). Utóbbi a képfeldolgozó eszköztáron (a vásznaktól balra) végzett beavatkozásoknak megfelelően mutatja az eredeti moiréfelvétel szürkeárnyalatos másolatán végzett szegmentáció aktuális fázisait. A képfeldolgozásból eredő adatvesztés minimalizálása érdekében a felhasználó számára az eredeti moiréfelvétel („*Original Image*“) mind-



10. ábra. A *Moiré Fringe Segmentation Tool* prototípusában végrehajtott szkeletonizáció eredménye



11. ábra. A *Moiré Fringe Segmentation Tool* prototípusában végrehajtott szkeletonizáció eredménye nagyítva (a) és átfedésben az eredeti moiréfelvétellel (b)

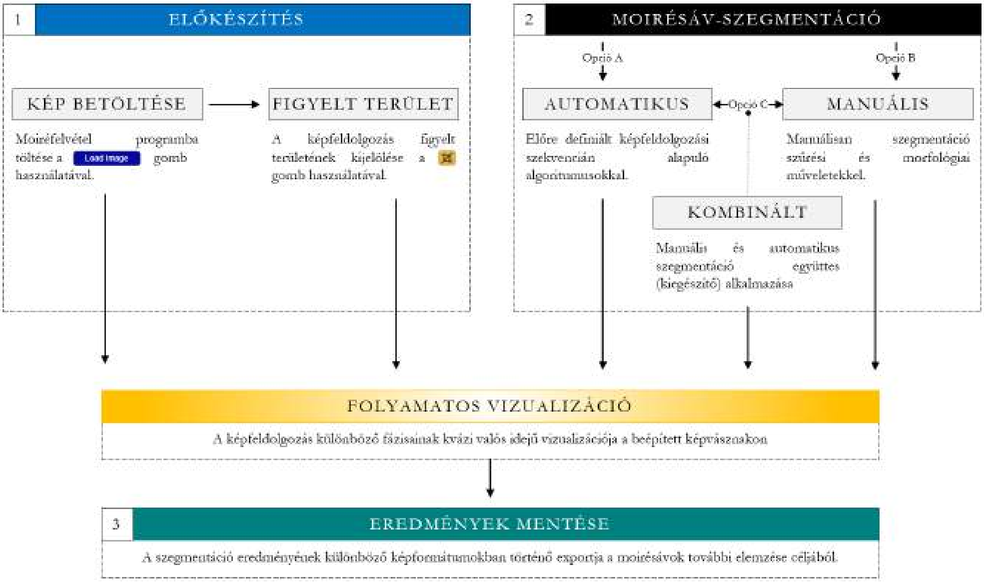


12. ábra. A *Moiré Fringe Segmentation Tool* prototípusába épített szegmentáló algoritmus eredménye nagyítva (az *"Algorithm 1"* gomb lenyomását követően)

végig látható marad. A két vászon alatt található kivágás gomb ⛶ használatával a bemeneti moiréfelvételek figyelt területének (ROI, *region of interest*) levágása végezhető téglalapkijelölő segítségével.

Képfeldolgozó eszköztár

Az MFST prototípusának képfeldolgozó eszköztára biztosítja a programba betöltött („*Load Image*“ a bal felső sarokban) moiréfelvételek QRT szűrési és morfológiai finomhangolásait. A prototípusba hét különböző képfeldolgozási művelet került beépítésre: (1) fényerőszabályzás, (2) kontrasztjavítás, (3) 2-D Gauss-féle elmosás, (4) küszöbölés, (5) hisztogram kiegyenlítés, (6) inverzió és (7) szkeletonizáció. Az (1-4) műveletekhez állítható vízszintes skálák tartoznak reset funkcióval ↺, az (5-7) műveletekhez pedig dedikált gombok tartoznak. Minden művelet QRT vizualizációt biztosít a vásznon („*Processed Image*“). Az összes képmódosítás visszaállítá-



Moiréfelvétel programba töltése a Load Image gomb használatával.

A képfeldolgozás figyelt területének kijelölése a ⛶ gomb használatával.

Előre definiált képfeldolgozási szekvencián alapuló algoritmusokkal.

Manuálisan szegmentáció szűrési és morfológiai műveletekkel.

Manuális és automatikus szegmentáció együttes (kiegészítő) alkalmazása

A képfeldolgozás különböző fázisainak kvázi valós idejű vizualizációja a beépített képvásznakon

A szegmentáció eredményének különböző képformátumokban történő exportja a moirésávok további elemzése céljából.

13. ábra. A *Moiré Fringe Segmentation Tool* prototípusában prototípusában történő szegmentáció folyamata sára szintén dedikált gomb ↺ szolgál. Mivel a javasolt szegmentálási módszer utolsó lépése, a szkeletonizáció megjelenítésére több módszer is implementálásra került, a szkeletonizáció gombjai a képfeldolgozó eszköztár alján, külön sorban jelennek meg. Ezek a gombok a szkeletonizációs folyamat eredményét három kontextusban jelenítik meg: (a) csak a szkeletonizált kép szerepel (*„Skeleton Only“*), (b) a szkeletonizált kép átfedésben az eredeti moiréfelvétel szürkeárnyalatos másolatával (*„Skeleton on Gray“*), (c) a szkeletonizált kép átfedésben az eredeti moiréfelvétellel (*„Skeleton on Original“*). A képfeldolgozás eredményei a következő formátumokban exportálhatók ki *„Save Image“* („kép mentése“) gomb használatával: (1) Windows Bitmap (*.bmp*), (2) JPEG 2000 (raw codestream, *.j2c*, *.j2k*), (3) JPEG 2000 (Part 1, *.jp2*), (4) Joint Photographic Experts Group (*.jpg, .jpeg*), (5) Portable Bitmap (*.pbm*), (6) Portable Graymap (*.pgm*), (7) Portable Network Graphics (*.png*), (8) Portable Pixmap (*.ppm*), (9) Sun Raster (*.ras*), (10) Tagged Image File Format (*.tif, .tiff*).

Beépített automata szegmentáló algoritmusok

A beépített algoritmusok képfeldolgozási műveletek előre definiált szekvenciáival végeznek önálló vagy a manuális szegmentációt kiegészítő delineációt. Az MFST prototípusába egyetlen algoritmus került beépítésre (*„Algorithm 1”*), amely az előzetes kutatásban bevezetett automatikus szegmentálási eljárást követi. Az *„Algorithm 2-5”* gombok a kutatás későbbi szakaszáig helyőrző (placeholder) szereppel bírnak. Az *„Adjust”* ↺ Adjust („igazítás”) gomb megnyomásával az automatikus algoritmusok által adott eredmények finomhangolása végezhető manuálisan.

MEGBESZÉLÉS

Az MFST prototípusa egy egyszerű, gyors, és a felvételek MS-jainak nagy részét pontosan lekövető szegmentációt tesz lehetővé. Ugyanakkor az eredményeket árnyalja, hogy a prototípusba épített szűrési és morfológiai műveletek, amellett, hogy biztosítják az adaptív és rugalmas szegmentáció feltételeit, jellegükből adódóan adatvesztéshez, ezáltal pontatlan és/vagy sporadikus delineációhoz vezethetnek. A prototípus általánosan megbízható használhatósága érdekében az adatvesztést mérséklő és a hatékonyabb adatkinyerést növelő szegmentációs célzatú funkcióbővítés szükséges. Az MFST továbbfejlesztésének lehetséges módjai (1) a dilatáció, azaz az előtérben lévő pixelek körüli régiók fokozatos növelése; (2) a képélesítéshez alkalmazható felüláteresztő szűrők; (3) adaptív küszöbölés lokális és globális átlagértékek alapján; (4) bitenkénti XOR műveletek alul- és túlkontrasztált moiréfelvételek alapján; (5) fuzzy logikai rendszer[39] a manuális és előre definiált algoritmusok kombinálásához; (6) nagy mennyiségű mintaadat alapján mély gépi tanulás (*deep learning*) útján fejlesztett automatikusan szegmentáló algoritmusok; valamint (7) komplex mintaelemzésre alkalmas gyors Fourier-transzformáció (*Fast Fourier Transform*, FFT).[43]

Az MFST-on alapuló képfeldolgozás természetesen nem váltja ki a röntgenfelvételek és más bevett képalkotó eljárások használatát, mivel különösen a fejlesztés első fázisában nem a scoliosis diagnosztikája, hanem a diagnosztikához megfelelő, szegmentált képi bemenet létrehozása a cél. Ez azt jelenti, hogy a szoftver a mai formájában a kutatások eszköze, így a potenciális felhasználói elsősorban a kutatás-fejlesztés számára hasznos bemenetet nyújtani képes egészségügyi és műszaki szakemberek. Ugyanakkor a jövőben, elegendő mennyiségű képi adat birtokában a gépi tanulás eszközével lehetőség nyílik arra, hogy az MS-ok szegmentációja automatikusan valósuljon meg. A megfelelő mennyiségű moiréfelvétel begyűjtésének és ezáltal a szoftver finomhangolásának hatékony és innovatív módja, mely járulékos haszonként az egészségtudatosság és a tudománykommunikáció céljait is szolgálja, az ún. *citizen science* (CS) módszertan bevonása. A CS lényege, hogy szakirányú tudományos képzettséggel nem rendelkező személyek végeznek adatgyűjtést tudományos projekteket támogatva, jellemzően kutató-fejlesztő intézmények orientációjával.[44] A CS mint adatgyűjtési módszertan az utóbbi évtizedekben elnyerte a tudományos közösség legitimációját, és az orvostudomány terén is számos valid eredmény köszönhető neki.[45] Az adatgyűjtésen túl a CS képessé teszi az állampolgárokat arra, hogy tudományos kérdéseket, sőt akár válaszokat fogalmazzanak meg, és megosszák adataikat a tudományos közösséggel. A polgárok választ adhatnak a betegeket és az egészségügyi rendszert egyaránt érdeklő népegészségügyi kérdésekre, így a CS az egészségügyi kutatások legitim módszere.[46] Az MFST esetében a célközönség várhatóan a mozgásszervi betegségek iránt érdeklődőkből (testnevelők, edzők, védőnők, iskolai egészségvédelmi szakemberek) és érintettekből tevődik össze. Másfelől a szoftver által biztosított manuális MS-szegmentáció finomhangolásába bevonhatók informatika és képfeldolgozás iránt érdeklődő, az átlagos felhasználói szintnél némileg magasabb IKT-kompetenciákkal rendelkező, kísérletezésre hajlandó állampolgárok. A prototípusba ágyazható analitikai rendszer segítségével felhasználói adatok gyűjthetők, amelyek hozzájárulnak a szoftver jövőbeni fejlesztéséhez. A kinyert adatok által lekövethetővé válnak a felhasználók módszerei és preferenciái – különösen a szegmentálás folyamatainak sorrendisége, az egérmozgás és a műveletekre szánt idők tekintetében. A szoftver alkalmazói részéről tekintélyes mennyiségű adat gyűjthető a felhasználói élményre vonatkozóan is, így ez a vetülete (UX) is hatékonyan fejleszthető, valamint esetleges működési rendellenességei (ún. bugjai) is könnyen feltárhatók.

Következtetések

Ebben a tanulmányban a scolioticus gerinc moirémintázatainak szegmentálására irányuló kutatás második fázisa valósult meg, amelynek keretében bemutatásra került a *Moiré Fringe Segmentation Tool* szoftver-alapú alkalmazás prototípusa MS-ok detektálására és kontúrozására. A prototípus a MS-ok szegmentációját kvázi valós időben manuálisan állítható szűrési és morfológiai képfeldolgozási műveletekkel, valamint előre meghatározott szekvencián alapuló, beépített algoritmussal támogatja. A kutatás első fázisához hasonlóan a szoftver alkalmazhatóságát egy egyszerű, gyors és a felvételek MS-jainak nagy részét pontosan lekövető szegmentálás igazolja. Az eredmények azt mutatják, hogy az MFST szoftver prototípusa megfelelő alapot nyújt a MS-ok szegmentációjára irányuló további, kiterjesztett képfeldolgozási műveletekkel operáló kutatás-fejlesztéshez. Egyszerűségének és gyors működésének következtében, a prototípus továbbfejlesztett megoldása helyettesítheti az időigényes és komplex szegmentálási módszereket is.

A szerzők részvétele: Kutatásvezető, kutatási célok meghatározása [Conceptualization]: B.CS. Adatgazdász, adatok kezelése és metaadatolása [Data curation]: B. CS. Kísérletvezető, adatgyűjtés lebonyolítása [Investigation]: B.CS. Módszertani szakember, modellalkotás [Methodology]: B.CS., H.E.G. Programozó, informatikai támogatás biztosítása [Software]: B.CS., M.A.D. Kutatási terv készítése és ellenőrzése, mentorálás [Supervision]: M.A.D., H.E.G., A.Á. Eredmények és módszertan ellenőrzése [Validation]: B.CS., H.E.G., M.A.D., A.Á., T-CS.M. Vizualizáció és adatmegjelenítés [Visualization]: B.CS. Eredeti kézirat megfogalmazása [Writing (original

draft)]: B.CS., H.E.G. Kézirat végleges változatának megfogalmazása, lektorálási folyamatok kezelése [Writing (review & editing)]: B.CS., H.E.G.

Köszönetnyilvánítás: A szerzők köszönetet mondanak a SALUS Orthopedtechnikai Kft. munkatársainak (Joó István, Prommer Katalin és Marlok Ferenc) a kutatáshoz szükséges moiréfelvételek rendelkezésre bocsátásáért.

Támogatás: A kutatómunka anyagi támogatásban nem részesült.

Összeférhetetlenség: Nincs.

Rövidítések: CS - Citizen Science (állampolgári tudomány); FFT - Fast Fourier Transform (gyors Fourier-transzformáció); IKT - Információs és Kommunikációs Technológiák; IR - infrared (infravörös); MFST - Moiré Fringe Segmentation Tool; MS - moirésáv (moiré fringe); MT - moiré topográfia (moiré topography); QRT - quasi-real-time (kvázi valós idejű); ROI - region of interest (figyelt terület); UX - user experience (felhasználói élmény); XOR - logical eXclusive OR (*kizáró vagy* logika).

IRODALOM

1. *Labecka MK, Plandowska M.* Moiré topography as a screening and diagnostic tool-A systematic review. PLoS One. 2021;16(12):e0260858.
2. *Czaprowski D, Stolinski Ł, Tyrakowski M, Kozinoga M, Kotwicki T.* Non-structural misalignments of body posture in the sagittal plane. Scoliosis Spinal Disord. 2018;13:6.
3. *Hawke F, Rome K, Evans AM.* The relationship between foot posture, body mass, age and ankle, lower-limb and whole-body flexibility in healthy children aged 7 to 15 years. J Foot Ankle Res. 2016;9:14.
4. *Evans AM.* The paediatric flat foot and general anthropometry in 140 Australian school children aged 7 - 10 years. J Foot Ankle Res. 2011;4(1):12.
5. *Martínez-Nova A, Gijón-Noguerón G, Alfageme-García P, Montes-Alguacil J, Evans AM.* Foot posture development in children aged 5 to 11 years: A three-year prospective study. Gait & Posture. 2018;62:280-4.
6. *Angarita-Fonseca A, Boneth-Collante M, Ariza-Garcia CL, Parra-Patiño J, Corredor-Vargas JD, Villamizar-Niño AP.* Factors associated with non-specific low back pain in children aged 10-12 from Bucaramanga, Colombia: A cross-sectional study. J Back Musculoskelet Rehabil. 2019;32(5):739-47.
7. *Calvo-Muñoz I, Gómez-Conesa A, Sánchez-Meca J.* Prevalence of low back pain in children and adolescents: a meta-analysis. BMC Pediatr. 2013;13:14.
8. *Filho JNdS, Batista LA, Gurgel JL, Porto F.* Shadow Moiré technique for postural assessment: qualitative assessment protocol by intra- and inter-rater evaluation. Journal of Physical Therapy Science. 2017;29(2):356-60.
9. *Silva JG, Almeida MSd, Costa CGd, Rocha AF, Silva PMd, Silva RTGd, et al.* Moiré topography: an alternative to scoliosis evaluation in student's health. Journal of Human Growth and Development. 2014;24:62-6.
10. *Negrini S, Donzelli S, Aulisa AG, Czaprowski D, Schreiber S, de Mauroy JC, et al.* 2016 SOSORT guidelines: orthopaedic and rehabilitation treatment of idiopathic scoliosis during growth. Scoliosis Spinal Disord. 2018;13:3.
11. *Caruncho MV.* The effects of diagnostic radiation. [Os efeitos da radiação diagnóstica]. Revista Brasileira de Medicina de Família e Comunidade. 2011;6(19):116-7. [Portuguese].
12. *Brent RL.* Carcinogenic risks of prenatal ionizing radiation. Seminars in Fetal and Neonatal Medicine. 2014;19(3):203-13.

13. *Lin EC.* Radiation risk from medical imaging. Mayo Clin Proc. 2010;85(12):1142-6; quiz 6.
14. *Knott P, Sturm P, Lonner B, Cahill P, Betsch M, McCarthy R, et al.* Multicenter Comparison of 3D Spinal Measurements Using Surface Topography With Those From Conventional Radiography. Spine Deformity. 2016;4(2):98-103.
15. *Guidetti L, Bonavolontà V, Tito A, Reis VM, Gallotta MC, Baldari C.* Intra- and Interday Reliability of Spine Rasterstereography. BioMed Research International. 2013;2013:745480.
16. *Zheng Y-P, Lee TT-Y, Lai KK-L, Yip BH-K, Zhou G-Q, Jiang W-W, et al.* A reliability and validity study for Scolioscan: a radiation-free scoliosis assessment system using 3D ultrasound imaging. Scoliosis and spinal disorders. 2016;11(1):13.
17. *Lai KK-L, Lee TT-Y, Lee MK-S, Hui JC-H, Zheng Y-P.* Validation of Scolioscan Air-portable radiation-free three-dimensional ultrasound imaging assessment system for scoliosis. Sensors (Basel). 2021;21(8):2858.
18. *Kwok G, Yip J, Yick KL, Cheung MC, Tse CY, Ng SP, et al.* Postural screening for adolescent idiopathic scoliosis with infrared thermography. Sci Rep. 2017;7(1):14431.
19. *Takasaki H.* Moiré topography. Applied optics. 1970;9(6):1467-72.
20. *Antal Á.* Optikai úton generált Moiréfelületek hibaanalízise és identifikálása méréstechnikai alkalmazásokkal. [Doctoral dissertation]: Budapesti Műszaki és Gazdaságtudományi Egyetem; 2009.
21. *Gréczy I, Sárkány J, Tóth J, Nemes J, Bakay A.* Scoliosos szürés Bács-Kiskun megyében Adams teszttel és moiré technikával. Orv Hetil. 1988;129(17):883-7.
22. *Petra B, Kata P, Ákos A.* Digitális moiré képek vizsgálata gerincferdüléses betegek nyomon követésére. Biomechanica Hungarica. 2014;7(1).
23. *Batouche M, Benlamri R, Kholladi M.* A computer vision system for diagnosing scoliosis using moiré images. Computers in Biology and Medicine. 1996;26(4):339-53.
24. *Adair I, Van Wijk M, Armstrong G.* Moiré topography in scoliosis screening. Clinical orthopaedics and related research. 1977;129:165-71.
25. *Ruggerone M, Austin JH.* Moiré topography in scoliosis. Correlations with vertebral lateral curvature as determined by radiography. Phys Ther. 1986;66(7):1072-7.
26. *Ápolási Szakmai Kollégium és a Magyar Gyógytornászok Társasága.* Az Egészségügyi Minisztérium szakmai protokollja. A scoliosis (az idiopathiás strukturális scoliosis) fizioterápiájáról. 2008. Available from: *http://www.gyogytornaszok.hu/regi/files/scoliosis_protokoll.pdf* [cited 2018 March 12].
27. *Yeras AM, Peña RG, Junco R.* Moiré topography: alternative technique in health care. Optics and Lasers in Engineering. 2003;40(1-2):105-16.
28. *Hertz H, Russomano T, Porto F, Steiger A, de Azevedo DF, Gurgel J.* Development of shadow Moiré technique as an alternative low-cost method for postural evaluation. Scientia Medica. 2005;15(4):235-42.
29. *Porto F, Gurgel JL, Russomano T, Farinatti PDTV.* Moiré topography: characteristics and clinical application. Gait & Posture. 2010;32(3):422-4.
30. *Patias P, Grivas TB, Kaspiris A, Aggouris C, Drakoutos E.* A review of the trunk surface metrics used as Scoliosis and other deformities evaluation indices. Scoliosis. 2010;5(12):20.
31. *Batouche M, Benlamri R, editors.* A computer vision system for diagnosing scoliosis. Proceedings of IEEE International Conference on Systems, Man and Cybernetics; 1994: IEEE.
32. *Kim HS, Ishikawa S, Ohtsuka Y, Shimizu H, Shinomiya T, Viergever MA.* Automatic scoliosis detection based on local centroids evaluation on moire topographic images of human backs. IEEE transactions on medical imaging. 2001;20(12):1314-20.
33. *Porto F, Gurgel JL, Russomano T, Farinatti PT.* Moiré Topography: From Takasaki Till Present Day. Recent Advances in Scoliosis: InTech Publications; 2012. p. 103-18.
34. *Ikeda T, Terada H.* Development of the moiré method with special reference to its application to biostereometrics. Optics & Laser Technology. 1981;13(6):302-6.

35. *Kim H, Ushijima H, Ishikawa S, Otsuka Y, Shimizu H, Shinomiya T, et al., editors.* Scoliosis detection based on difference of apexes position and angle on Moiré topographic images. International Congress Series; 2004.
36. *Balla P, Manhertz G, Antal A.* Diagnostic moiré image evaluation in spinal deformities. Optica Applicata. 2016;46(3).
37. *Zhi H, Johansson RB.* Interpretation and classification of fringe patterns. Optics and lasers in engineering. 1992;17(1):9-25.
38. *Zhi H, Johansson R, editors.* Interpretation and classification of fringe patterns. 11th IAPR International Conference on Pattern Recognition Vol III Conference C: Image, Speech and Signal Analysis; 1992: IEEE Computer Society.
39. *Woo WH, Yen KS.* Moiré Fringe Segmentation Using Fuzzy Inference System. In: Ibrahim H, Iqbal S, Teoh S, Mustaffa M, editors. 9th International Conference on Robotic, Vision, Signal Processing and Power Applications Lecture Notes in Electrical Engineering; Singapore: Springer; 2017. p. 247-55.
40. *Bogdán C, Magony AD, Wolgang B, Antal Á, Tunyogi-Csapó M.* Segmentation of moiré fringes of scoliotic spines using filtering and morphological operations. Acta Polytechnica Hungarica, (accepted for publication). 2023.
41. *Wiklund ME, Wilcox SB.* Designing usability into medical products: CRC Press; 2005.
42. *MATLAB. (2018).* 9.5.0.944444 (R2018b). Natick, Massachusetts: The MathWorks Inc.
43. *Hladnik A, Muck D, Stanić M, Černič M.* Fast Fourier Transform in Papermaking and Printing: Two Application Examples. Acta Polytechnica Hungarica. 2012;9:155-66.
44. *Vohland K, Land-Zandstra A, Ceccaroni L, Lemmens R, Perelló J, Ponti M, et al.* The science of citizen science: Springer Nature; 2021.
45. *Wiggins A, Wilbanks J.* The rise of citizen science in health and biomedical research. The American Journal of Bioethics. 2019;19(8):3-14.
46. *Petersen C, Austin RR, Backonja U, Campos H, Chung AE, Hekler EB, et al.* Citizen science to further precision medicine: from vision to implementation. JAMIA Open. 2019;3(1):2-8.

Revista Lusófona de Estudos Culturais / Lusophone Journal of Cultural Studies, Vol. 9, No. 2, 2022, pp. 119–135
https://doi.org/10.21814/rlec.3996

BOTTOM-UP AND RECIPROCAL CITIZEN SCIENCE: UNTAPPED RESOURCES OF NOVEL IDEAS. PRELIMINARY EXPERIENCES OF A CITIZEN SCIENCE AS PUBLIC ENGAGEMENT PROGRAM

Evelin Gabriella Hargitai
Institute of Transdisciplinary Discoveries, Medical School, University of Pécs, Pécs, Hungary
Conceptualization, investigation, methodology, writing – original draft, writing – review & editing

Attila Sik
Institute of Transdisciplinary Discoveries, Medical School, University of Pécs, Pécs, Hungary
Funding acquisition

Alexandra Samoczi
Institute of Transdisciplinary Discoveries, Medical School, University of Pécs, Pécs, Hungary
Project administration

Milan Hathazi
Institute of Transdisciplinary Discoveries, Medical School, University of Pécs, Pécs, Hungary
Methodology

Csaba Bogdán
Medical School, University of Pécs, Pécs, Hungary
Conceptualization, methodology, writing – original draft

ABSTRACT

In scientific research, citizen science is widely regarded as an involvement of the general public in scientific research initiated by universities, scientific organisations or research centres. In this top-down approach (top-down citizen science), participating citizens usually collect data or provide samples for research — that is, they are considered volunteer research assistants following instructions. This study analyses alternatives of top-down citizen science: one, widely known, which is the bottom-up way of citizen science and another, the reciprocal approach suggested by the authors. Bottom-up is based on local initiatives and is constituted by community-led projects. For bottom-up citizen science, scientific organisations may provide methodological and organisational frames. However, the idea and the implementation remain in the competence of the participant citizens. Reciprocal citizen science emerged from a need for a more holistic policy toward citizen science. As part of this, identifying viable citizen-initiated projects, measuring their scientific and/or innovation potential, and integrating them into a citizen science mentor program are questions to be systematically discussed and solved. This study addresses methodological challenges in mentoring citizen science projects, covering a mentor training concept for citizen science designed by the Institute of Transdisciplinary Discoveries. Encouraging citizen research is needed for a new impetus to scientific discoveries. The perspectives of people with no scientific background can also advance problems — mainly those that require fresh and unbiased approaches. Citizen science may also be a solution for leveraging the knowledge of science leavers.

KEYWORDS

citizen science, mentoring, bottom-up citizen science, empowerment

Ciência Cidadã Recíproca e de Baixo Para Cima: Recursos Inexplorados de Novas Ideias. Experiências Preliminares de um Programa de Ciência Cidadã Como Envolvimento Público

Resumo

Na pesquisa científica, a ciência cidadã é amplamente considerada como o envolvimento do público geral em pesquisas científicas iniciadas por universidades, organizações científicas ou centros de investigação. Nessa abordagem de cima para baixo (ciência cidadã chamada top-down), os cidadãos participantes geralmente recolhem dados ou fornecem amostras para pesquisa — ou seja, são considerados assistentes voluntários de pesquisa que seguem instruções. O presente estudo analisa alternativas de ciência cidadã top-down: uma, amplamente conhecida, que é o método bottom-up (de baixo para cima) da ciência cidadã e outra, a abordagem recíproca sugerida pelos autores. Bottom-up é baseado em iniciativas locais e é constituído por projetos liderados pela comunidade. Para a ciência cidadã de baixo para cima, as organizações científicas podem fornecer estruturas metodológicas e organizacionais. No entanto, a ideia e a implementação continuam a pertencer à competência dos cidadãos participantes. A ciência cidadã recíproca surgiu da necessidade de uma abordagem mais holística da ciência cidadã. Como parte disso, identificar projetos viáveis, medir o seu potencial científico e/ou inovativo e integrá-los a um programa de mentores de ciência cidadã são questões a serem discutidas e resolvidas sistematicamente. Este estudo aborda desafios metodológicos na mentoria de projetos de ciência cidadã, abrangendo um conceito de formação de mentores concebido pelo Instituto de Descobertas Transdisciplinares. Incentivar a pesquisa dos cidadãos é necessário para dar um novo impulso às descobertas científicas. As perspectivas de pessoas sem formação científica também podem trazer problemas — principalmente aqueles que exigem abordagens novas e imparciais. A ciência cidadã também pode ser uma solução para alavancar o conhecimento dos que abandonaram a carreira científica.

Palavras-chave

ciência cidadã, mentoria, ciência cidadã de baixo para cima, empoderamento

1. Introduction: Citizen Science As Public Engagement

1.1. Bottom-Up Citizen Science: From Science Communication to Involvement of the Public in Scientific Activities

The trend of universities moving from entrepreneurial to civic universities indicates that higher education institutes recognised the necessity of embeddedness of education and scientific organisations in society. The involvement of non-scientifically qualified citizens in scientific projects goes back to the mid-1990s (Vohland, Göbel et al., 2021), although, in the 1920s, citizen involvement in scientific questions was also described by the term "scientific citizen" (Cohen, 1920). Initially, people volunteered their time and energy to help with various research projects. Despite the many decades of history, "citizen science" (CS) and "citizen scientist" expressions first appeared in the *Oxford English*

Dictionary in 2014. The dictionary describes it as: CS as a “scientific work undertaken by members of the general public, often in collaboration with or under the direction of professional scientists and scientific institutions” (Haklay, 2014, para. 4). Citizen scientist as “a member of the general public who engages in scientific work, often in collaboration with or under the direction of professional scientists and scientific institutions; an amateur scientist” (Haklay, 2014, para. 6).

CS emerged from the recognition that science, technology, and innovation could respond better to environmental, social and economic challenges if a wider circulation of scientific findings is ensured. It is possible when local, national, regional and global participation in the research is available for any entity of the society. Since the first appearance of the expression CS in the literature, its meaning has changed. New expressions emerged to describe the level of involvement of citizens in scientific projects. The most common form of CS to date is when a university or other academic institution encourages citizens to collect data for research initiated by a person or institution with authority in the scientific field. That is the so-called top-down (TD) approach of CS. TD CS often serves for observing or monitoring environmental phenomena, and data are used at the national or international level (cf., Eicken et al., 2021, p. 468).

Bonney et al. (2009) developed an often-used categorisation of CS projects. Their framework defines:

- *contributory* projects as projects where scientists design the project and participants are involved in collecting and analysing data according to predefined protocols;
- *collaborative* projects, participants may also be involved in adjusting protocols, drawing conclusions, and proposing new directions for research;
- *co-created* projects include citizens in all stages of the scientific process; scientists and citizens collectively design and develop the project.

Another categorisation often cited is based on the levels of participation. In Haklay’s (2013) classification, levels range from

- citizens as *sensors* (crowdsourcing), and
- citizens as *interpreters* (distributed intelligence),
- to levels where participants are more involved in problem definition and collection protocols (participatory science) or are *even part of the entire development of the scientific process* (extreme CS).

Growing dissatisfaction within academia and industry hot environmental and societal topics of interest to the public, leading to the more active participation of the public in science. The UNESCO Recommendation on Open Science (2021) is one of the most important international documents, stating that science must be open to the widest possible public and that scientific data from stakeholders must also be incorporated into research. Open science (broadly in line with the concept of CS), according to the recommendation,

> should not only foster enhanced sharing of scientific knowledge but also promote inclusion of scholarly knowledge from marginalised groups (such

> as women, minorities, Indigenous scholars, non-Anglophone scholars, scholars from less-advantaged countries) and contribute to reducing inequalities in access to scientific development, infrastructures and capabilities among different countries and regions. (UNESCO Recommendation on Open Science, 2021, p. 5)

This approach is the same as that represented by the so-called bottom-up (BU) CS. BU CS is a growing method of public engagement with science, in which citizens perform scientific activities, including data collection or even complex research, in order to address local and global issues. Contrary to TD CS projects in which citizens collect data in institutionally controlled projects, the BU approach is citizen-initiated. “Observing or monitoring efforts defined and undertaken at the local scale and brought forward to higher-level bodies, often with a focus on supporting outcomes desired by a local community” (Eicken et al., 2021, p. 468).

1.2. Criticism of Top-Down Citizen Science

In general, citizens can engage in different levels of the scientific process, including the development of research questions and hypotheses, data collection, data analysis, drawing conclusions, and disseminating data. The most popular form of CS, as described above, is when citizens collect data under the direction of professional scientific institutions (TD approach, cf., Haklay et al., 2021, pp. 15–18). In these scientist-led projects, the level of citizen engagement varies but is limited: citizens can be involved only in data collection, or they can analyse and evaluate gathered data. The advantage of this type of CS is that professionals regulate research projects. Therefore, the collected data are more reliable. Some critics of TD CS mention that these projects exploit citizens by making them collect data and/or be scientific assistants for free, or these projects do not give eureka moments to citizens (Vohland, Land-Zandstra, et al., 2021, pp. 2, 5). In addition, the TD CS strategy emphasises unequal relationships between the academic sector and the citizens. Although it can be viewed as an exercise to connect research and citizens, it rarely allows ordinary citizens to peek behind the doors of a research lab or institute. Thus it is an insufficient exercise to break down the “ivory tower” image of universities. However, some researchers continue to suggest that valid scientific results can only come from scientist-led research legitimised by a scientific institution (Haklay, 2013).

Universities in the most developed countries exercise the civic university ethos and even integrate citizens actively in the design and planning of the research (Follett & Strezov, 2015; Haklay et al., 2021, p. 14). Therefore, we find some examples of scientific institutions supporting the BU approach. The most typical BU projects are more active (and activist) because citizens lead their own projects, which are mostly related to solving some community problems or needs, but in most cases, the idea or the encouragement is from a scientific institute (Ostermann-Miyashita et al., 2021, p. 5). BU type of CS is focused on the needs of stakeholders.

However, BU has weaknesses as well. The danger of BU projects is that the citizens can be personally involved and/or interested in the project, so they can easily be biased. Another difficulty is that they do do-it-yourself research without sufficient scientific methodological knowledge resulting in wasted efforts and outputs that the scientific community cannot accept, further inserting a wedge between the research and citizen community.

BU calls attention to the potential of citizens' own discoveries and suggests that the role of scientists can also be supportive. In BU projects, citizens can approach scientists looking for assistance with their projects.

Citizens can also be involved in scientific projects in a more extreme way than BU. In the extreme CS approach (Haklay, 2013), participants try to design and develop new devices and knowledge creation processes that can be useful for society, considering local needs, practices, culture and works. It enables any community, regardless of their literacy or scientific qualifications. Stakeholders can be an active part of the whole process — from problem definition, data collection, and analysis, and visualisation to action. Therefore, those people who do extreme CS are empowered to be part of the entire development of the scientific project. Of course, using this method, there is a threat that citizens use scientific data from unchecked sources or draw incorrect conclusions. That is particularly dangerous when citizens are involved in sensitive local affairs as hobby researchers.

Given the above, there is a need for an approach to CS that builds on stakeholder issues but works with a methodology that meets the highest possible scientific criteria. In our paper, we propose such an approach by combining the benefits of TD and BU CS.

2. METHODS OF RECIPROCAL CITIZEN SCIENCE

A novel approach to CS, the so-called "reciprocal CS" (RCS), introduced by the Institute of Transdisciplinary Discoveries (ITD), University of Pécs, Hungary, in the "International Transdisciplinarity Conference" (Sík et al., 2021), combines the advantages of TD, and BU approaches. RCS is based on citizen-initiated research ideas and is citizen-led. In order to avoid pseudoscientific or biased approaches, the university (or other scientific institution) provides scientific support, especially in the field of methodology and equipment, if needed. RCS differs from the BU approach in that the former is more organised and systematised due to the supervision and because the support provided for the citizens is useful for the university as well because it helps to elaborate more modern and efficient ways of scientific mentoring and it can lead to novel approaches of scientific problems. We call this approach reciprocal (see Table 1) because the university also benefits from a research project that solves a local community or even individual problem. In RCS, the source of the research idea is the citizen, and the role of the scientific institution is support, encouragement, and scientific coaching (research design, methods, scientific presentation and writing). If the citizen needs it, the institution can provide equipment as well.

APPROACHES TO CITIZEN SCIENCE	MOTIVATION	STAKEHOLDER BENEFIT	METHODOLOGICAL ACCURACY	SCIENTIFIC NETWORKING	MAIN CHARACTERISTICS
Top-down	↓	↓	↑	↑	Citizens involved in data collection Research regulated by professionals
Bottom-up	↑	↑	↓	↓	Projects based on citizens' ideas and needs Research regulated by citizens
Unleash your inner scientist (reciprocal citizen science)	↑	↑	↑	↑	University encouraged and supported projects Citizen-initiated topics and citizen-led research

Table 1 *Reciprocal citizen science compared to top-down and bottom-up approaches*

RCS can be implemented through a comprehensive *mentoring programme*. In the field of CS, almost all the mentoring programmes represent the TD approach. That is, a scientific institution prepares the citizens for the scientific data collection and possibly for the use of the application or other data organisation solution that the institution uses for the scientific research (cf., Haklay 2013). A huge difference from TD mentoring programmes is that in RCS, citizens get specific mentoring according to their needs. After an initial assessment, similar to a placement test, the mentoring program's organisers decide what training the mentee needs. In addition to developing research methodology, scientific database searching, scientific writing, and presentation skills, mentees can be provided with entrepreneurship coaching and incubation programmes if their ideas are worth enlarging into a startup.

The main novelty of the RCS approach is that it applies citizen engagement through mentoring. RCS encourages citizens to bring their own ideas to scientific institutions, which provides them mentoring, and support and gives scientific assistance tailored to the needs of the citizen. RCS uses a BU methodology because incubated research projects are based on citizens' ideas. They initiate and lead their own projects based on local or own interests or public issues. However, RCS uses the advantage of the TD approach to the extent that it is academy-encouraged and -supported. In addition, RCS provides methodological knowledge, research tools and infrastructure and entrepreneurial training in the case of projects with innovation potential. This multifaceted approach encourages citizens to publish their results or start a venture in the business field.

Considering that this combination of TD and BU approaches, by its very nature, leads to mutual knowledge and experience exchange among all levels of academic representatives and citizens, we define our approach as RCS. ITD of the University of Pécs elaborated a RCS mentoring program with the title of Unleash Your Inner Scientist. Unleash Your Inner Scientist is a transdisciplinary program that provides a mentoring framework for supporting citizen-initiated and -led scientific and innovation projects while developing a complete, practical-based methodological strategy for the scientific mentoring of citizens. Unleash Your Inner Scientist is currently in the pilot phase. It combines the benefits of TD and BU, making it RCS-based and unique in that it provides a comprehensive mentoring program for citizens, which aims to make the scientific or innovative results developed in the program known to the general scientific public. The scientific institute's role is to provide support and scientific coaching (research design, methods, scientific presentation and writing), equipment and entrepreneurship coaching (if needed). At the societal level, the RCS-based mentoring program's benefit is the encouragement of civic activism in a scientific way avoiding or at least controlling pseudoscience.

2.1. Advantages of Reciprocal Citizen Science in Approaching the University and Society

2.1.1. Reciprocal Citizen Science As a Transdisciplinary Method

Since CS is conducted by lay people, or at least by people who do not practice scientific research within an institutional, standardised framework, it is surprising that there are few CS mentoring programs. We can find among the few examples a mentoring and training program for open science ambassadors whose purpose is to empower citizen scientists to become effective open science ambassadors in their communities. However, this project is only for life science. Other CS mentoring programmes are focused on TD approaches and training citizen scientists as data collectors.

RCS offers a novel approach to CS and opens opportunities for involving lay people more extensively in science while maintaining all the advantages of the TD and BU approaches as researchers-led projects. Also, civil activism and social innovations remain viable. This approach exploits the citizens' scientific and/or innovation potentials while consistently contributing to their skill development. Importantly, the RSC implements a crucial aspect of the citizen-academy relationship: transdisciplinarity. When universities or research institutes look beyond the organisation's wall and seek the involvement of external stakeholders, then they create transdisciplinary projects and implement what is in the ethos of the civic university model.

2.1.2. Reciprocal Citizen Science As Innovation Potential

RCS can be embedded in the civic university approach. Civic university (Goddard et al., 2016) is based on the societal embeddedness of the university, when higher education institutes collaborate with local area and community, in partnership with local organisations, taking social responsibility.

The overall goal of RCS is to create a new way of citizen involvement in scientific research. Even the most extreme citizen involvement approach, the idea to be developed is either created or co-created by a scientist neglecting the huge potential of the non-scientific community. Considering that scientists make up only a small fraction of the adult human population, it would be unreasonable to think that citizens are not full of ideas that have *innovation potential*. In this project, we tap into this pool of ideas by creating the citizen-led project development approach. This unique approach also has a *knock-on effect on the academia-public relationship*. Since universities gradually move to "civic university" engagement recognising the embeddedness of universities in society, this approach brings the two sectors closer together. It builds trust in the academic sectors from the civil and general public points of view.

The core concept is that the knowledge and innovation potential of lay and/or non-scientific people often do not receive enough visibility, although many inventions and discoveries are also tied to these people. The knowledge generated by these people cannot be ignored in the information society.

> Involving citizens and broader communities beyond universities and traditional research institutions as participants in research systems has been defined as one of the megatrends that will influence future research policy. There is an increasing focus on how laypeople and other communities outside of traditional research institutions can be involved in all levels of research activities, including data collection and categorisation. (Magnussen, 2017, p. 394)

There are few researchers in society, so in scientific research and innovation, it would be a waste to miss someone who is not an institutional researcher.

Laypeople's inventions cannot be underestimated because some of them changed humanity. For example, the first operational aircraft was invented by the Wright Brothers. In these projects mentoring plays a crucial role in the success and effective progression.

RCS's development goals align with the *most in-demand core skills for work and life*. According to the *Future of Jobs Report 2020* of the World Economic Forum (2020), some of the top skills for 2025 are analytical thinking and innovation, active learning and learning strategies, complex critical thinking and analysis, problem-solving, creativity, originality and initiative, reasoning, problem-solving and ideation. Besides individual skill development, RCS is expected to have impacts at several levels in the lives of individuals and smaller or larger communities.

2.1.3. Reciprocal Citizen Science As Bridge of the Gender Gap

Even in the 21st century, relatively few women choose a career in science, and many leave the research career. According to UNESCO Institute for Statistics (2019) data, less than 30% of the world's researchers are women and women leave science careers in greater numbers than men. CS is an ideal option for women who do not have the time or opportunity to conduct scientific research professionally but would continue their previously discontinued research or embark on a career in science and/or innovation. In this way, these women can satisfy their desire for scientific success and have the opportunity to develop their ideas. Because the RCS can be done on a flexible schedule, it also fits into the agenda of mothers with children. Our preliminary market research shows the same: 62% of the respondents are female. Therefore, RCS can reduce the gender gap, providing empowerment to women and other underrepresented genders in scientific research. RCS can also be a solution for disadvantaged citizens who have not had access to higher education or cannot engage in scientific research due to financial constraints.

2.1.4. Reciprocal Citizen Science As Empowerment of Less-Advantaged Communities

RCS is not only able to solve local social and environmental problems but also to bring more citizens closer to academia. In the long run, this could even reduce university dropouts. Eurostat (2018) data show that 25% of students drop out of universities in the European Union. That means millions of students in a few years who will no longer make use of their academic knowledge after a few years. If a small portion of this group can be kept in the circle of scientific thinking with the help of RCS, it means that the knowledge taught at the university is not wasted, nor is it such a loss for individuals. The advantages of RCS are deepening and expanding scientific knowledge, improving understanding of research methods, deepening and expanding their knowledge of scientific research methodology, strengthening their researcher confidence, and developing their presentation and scientific writing skills. Moreover, what is important from the point of view of the labour market, is increased potential for career mobility and promotion and the opportunity to be in a supportive environment in which successes and further development opportunities can be evaluated. RCS provides people networking opportunities and empowerment.

2.1.5. General Motivational Factors

To better understand why people are participating in CS projects and why CS projects can attract people from non-scientific communities, firstly, we need to understand why people do voluntary activities. The following six motivational factors (volunteer functions inventory; Clary et al., 1998) can give us an explanation:

1. values — a possibility to express altruistic and humanitarian values;
2. understanding — an opportunity to earn knowledge, skills, and abilities;
3. social — an opportunity to strengthen and develop relations with others;
4. career — an opportunity to gain career-related benefits from volunteering activities;
5. protective — an opportunity to reduce guilt over being more fortunate than others;
6. enhancement — a possibility to aid the ego to grow and develop.

Therefore, CS is an ideal voluntary activity because CS projects can be based on altruistic and/or community goals, and at the same time, citizens' research activities can widen their knowledge base. CS provides an ideal opportunity to develop social relations, that is, in a local community. Citizens' projects often need new competencies which can be used in the labour market as well, and, hopefully, and this is not a very utopian idea, CS can contribute to the citizen's personal development.

Parthenos (2019) also collected CS's benefits for the citizens. These outcomes, of course, are ideally aligned with participant motivations:

- new/increased scientific knowledge and understanding;
- building/belonging to a community; social learning;
- empowerment;

- raised awareness;
- data access;
- development of personal capacities — the experience of self-efficacy and a sense of purpose.

These benefits are especially true if the CS project is implemented in an organised manner, linked to monitoring, and the citizen receives scientific assistance. Therefore, we believe that RCS is the ideal form of CS because it includes organised supervision and assistance for the citizens, and all the support is tailored to citizens' needs.

2.1.6. Reciprocal Citizen Science As a Solution for Burnout of Academic Researchers

RCS brings benefits not only to citizens but also to academic institutions. Involving university researchers in CS projects, such as mentors, can help them think from a broader perspective and face new social, environmental or other issues. Burnout in researchers and academics is a little-studied phenomenon. One of the best-known theories of burnout was provided by Maslach and Jackson (1982). They reveal the burnout phenomenon in three dimensions: first, emotional exhaustion (which is the leading symptom of burnout and suggests that the person's deep emotional resources have run out). Second, negative attitudes and impatience towards clients, colleagues and the job itself and third, reduced sense of effectiveness (a high degree of negative self-esteem is also associated).

While in other sectors of the economy, employees are increasingly appearing as key players in corporate performance, as their competence, efforts, motivation and commitment fundamentally affect competitiveness, the key role of employees in educational organisations is uninteresting for the employer in this respect (Jármai, 2018, p. 116). Large companies (especially multinational companies) are taking more and more serious care to organise their employees' mental, physical, and rest needs. However, there is no organised opportunity for teachers to discuss problems, supervise, maintain and develop their own personalities (work equipment). So, because of this feature, the quality of work can only be assessed indirectly, as there is no acceptable, standardised way or consequence of direct superior and student assessment, or not even its social recognition. Education plays a key role in society. The subjective well-being of its workers hardly preoccupies economic, professional, or even institutional decision-makers. There are aspirations for change and initial attempts to introduce various incentive systems to motivate employees based on performance to improve their work, but the information they receive reflects a mixed experience. The basic condition of subjective well-being is the feeling of satisfaction arising from professional self-fulfilment and self-realisation.

Burnout caused by overload particularly affects researchers in the science, technology, engineering, and math sectors (Site, 2017). Burnout is a direct consequence of competition. When scientists reach their goals, win an award, or are promoted, those successes help their recovery from stress. However, scientists' lives consist of more unsuccess and lack of time and money, or even the lack of positive feedback are extra factors of burnout.

Among the solutions to mental burnout, in addition to consulting a professional and having more rest, we also find knowledge transfer. A *Nature* article from 2020 (Gewin, 2020) encourages researchers to spread their knowledge. The article emphasises the importance of knowledge transfer not only from the societal point of view. The author believes that knowledge sharing helps researchers achieve a more balanced mental state. From this, we can deduce that CS is a possible form of researcher burnout prevention or treatment. Of course, it is not the only solution, but it can expand the repertoire of offerings and societal functions of universities. Another important factor in academic burnout is that the researchers need to build relationships for recognition. Publications and conference presentations are often exhausting for researchers (Site, 2017). CS offers a more relaxing network because it is based on more informal relationships and communication forms.

CS offers a new kind of connection for researchers, in which they do not need to solve difficult scientific tasks but can use their existing knowledge, learn new perspectives, and successfully solve scientific or social problems. Positive impacts of RCS for researchers as mentors are different and vary a lot according to their motivation and fields of interest. In general, scientists may encounter approaches to scientific phenomena and problems, which can serve as an inspiration even in their own research careers through challenging discussions with people who have fresh perspectives. Academic lecturers can benefit from developing their mentoring (communication, interpersonal, conflict management) skills by expanding their mentoring tools. The out-of-the-box thinking can provide them opportunities to test new ideas and gain further knowledge, improve their ability to share experience, knowledge, competencies and skills, and capacity to motivate another person. Finally, RCS provides a potential to renew enthusiasm for their role as experienced researchers and opportunities to reflect upon and articulate roles and responsibilities.

3. Preliminary Experiences of a Reciprocal Citizen Science-Based Mentoring Program

3.1. Unleash Your Inner Scientist Program

Combining the benefits of TD and BU and implementing an RCS-based practice, ITD of the University of Pécs elaborated an RCS mentoring program titled Unleash Your Inner Scientist. It provides a comprehensive mentoring program for citizens which aims to make the scientific or innovative results developed in the program known to the general scientific public. The scientific institute provides support, scientific coaching (research design, methods, scientific presentation and writing), and equipment and entrepreneurship coaching (if needed). At the societal level, the RCS-based mentoring program's benefit is the encouragement of civic activism in a scientific way avoiding or at least controlling pseudoscience.

Unleash Your Inner Scientist is based on transdisciplinarity, providing a mentoring framework for supporting citizens' scientific and innovation projects through a complete, practical-based methodological strategy for empowering local initiatives. The project aims at the general public (lay people, citizens) interested in science to develop primarily their scientific and, secondarily, their entrepreneurial and communication skills. The programme aims to support citizens in elaborating their area of interest on a scientific level, however, without integrating them into formal educational frameworks. The core element of the programme, that is, the citizen empowerment process, uses the tools of scientific and business mentoring, coaching and project consultation and provides scientific training to citizens (mentees). Parallelly, another important part of the core element is network building for mentors who form a learning community, sharing methodological expertise and the experience generated during the mentoring process. The experience share is cyclic: the experience and data collected in the pilot are used in the second cycle and so on (see Figure 1).

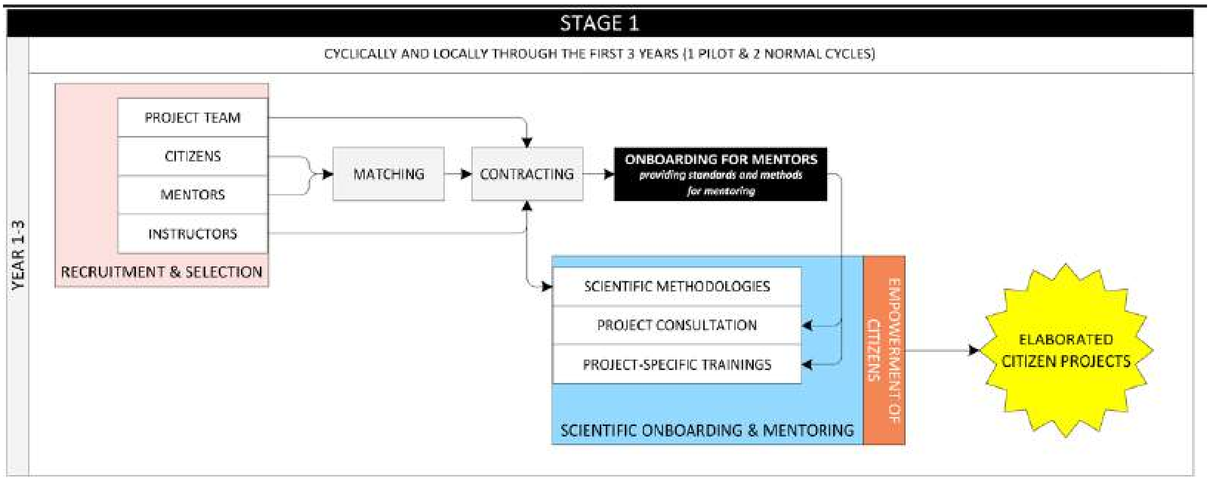


Figure 1 *Unleash Your Inner Scientist's process*

The advantage of the mentoring method is that the mentees (citizens) are supported by involving them as active leaders in their own learning and developing processes.

Beyond the project-specific scientific mentoring support, it is also reasonable to apply coaching methods and tools to encourage and empower citizens and tackle the natural anxiety that former experiences in institutional learning can cause.

Since the individuals in the target public may have no or only rudimentary experiences in scientific research, mentoring is preceded by a capacity-building programme where basic scientific knowledge is learned (research methodology, academic writing, scientific presentation). Besides basic scientific training, the programme includes a mini-course on entrepreneurial skills and knowledge development for those who want to launch a startup based on their innovation. The capacity-building programme is provided by an instructor board.

Onboarding, mentoring and continuous supervision is provided for mentors as well, in order to provide them with standards and methods and develop their mentoring-coaching skills and help them work effectively with citizens from potentially different backgrounds.

3.2. Preliminary Experiences of Unleash Your Inner Scientist

Unleash Your Inner Scientist is currently in the pilot phase. The pilot is based on *preliminary market research* made in Hungary by ITD. A quick quantitative and qualitative survey assessed potential mentees' needs and research interest areas. A total of 52 people with specific research ideas showed interest in the mentoring program. The main needs of citizens ($n = 52$) are mentoring and scientific consulting (90% of respondents marked this need), access to scientific databases (49%), financing (49%) and access to laboratories (20%). About 43% of the potential mentees are willing to do research in the field of psychology, and 25% want to conduct a project in cultural studies, followed by literary studies (18%) and other fields (14%). That means that, according to the needs assessment results, citizens need not expensive tools but rather scientific guidance.

The pilot program started in June 2022 with three mentees, but ITD formed a consortium with five European universities that would apply the same project in their local communities. The three mentees were selected by simple criteria: motivation, immediate availability of mentors and, for practical reasons, organisers selected proposals without the need for specific tools.

The pilot's preliminary experience shows that the mentees started the program with good basic knowledge and methodological background. The organisers and mentors of the program had the preliminary assumption that among the applicants, there would be a large proportion of people with pseudoscientific views or at least very simplistic scientific attitudes. It did not turn out that way. The three mentees are strongly committed to their research and are motivated to learn about scientific research methodologies.

3.3. Sustainability and Impact Measurement of the Unleash Your Inner Scientist Programme

The project's sustainability is based on, among others, the inclusion of prototyping environments (makerspaces or FabLabs) in the process. Citizens whose projects require tools and equipment can use the resources of the university's subcontracted local prototyping institution(s). Moreover, a digital infrastructure will be developed that allows citizen scientists to identify, obtain, and set up the technical aspects of their work (which today virtually always include a digital component in hardware or software, and usually both) and to document them with scientific rigour to support replicability and further research. The tailor-made Unleash Your Inner Scientist knowledge and data infrastructure for CS projects addresses the key challenges in citizen scientists' successful engagement in obtaining and documenting the "materials and methods" for their work.

CS can have broad-spectrum effects, influencing science itself and having societal, environmental, and economic impacts. However, as Somerwill and Wehn (2022) emphasise, in many CS projects, impact assessment is simplistic. After a systematic literature review, the authors identified best practices and approaches for measuring attitudes, behaviour and knowledge change in environmental CS projects. However, this approach, although it criticises superficial impact assessment practices, uses a qualitative method. Therefore, ITD elaborated a quantitative approach for measuring Unleash Your Inner Scientist's impact. The method can be applied to other projects as well.

The method is based on a quantitative questionnaire. The mentees fill out the questionnaire at the beginning and end of the mentoring programme, and the change over time is assumed to show the project's impact. In order to ensure the accuracy of the measurement, we use a control group which does not get any scientific mentoring. One part of the questionnaire is an attitude measurement related to science and the university, and in the other part, the mentees must analyse case studies from the point of view of which scientific research methods they would use.

4. Conclusion

The literature on CS has been analysing the potential of BU CS for years. RCS offers more than BU in that it includes more organised scientific oversight, which prevents citizens' projects from pseudoscience, and offers reversible benefits for scientific institutions. Examples of such benefits are reducing research burnout and the application of new scientific and innovative perspectives. RCS is also worth introducing in an international context because of various successful CS projects, although the vast majority are based on the TD approach. RCS offers an important component to CS: organised mentoring has been missing from a significant proportion of CS projects. RCS not only provides benefits to the academic sectors but also has the potential to improve the critical thinking skills of citizens, thus reducing the spread of pseudoscience on a large scale.

References

Bonney, R., Cooper, C. B., Dickinson, J., Kelling, S., Phillips, T., Rosenberg, K., & Shirk, J. (2009). Citizen science: A developing tool for expanding science knowledge and scientific literacy. *BioScience*, *59*(11), 977–984. https://doi.org/10.1525/bio.2009.59.11.9

Clary, E. G., Snyder, M., Ridge, R. D., Copeland, J., Stukas, A. A., Haugen, J., & Miene, P. (1998). Understanding and assessing the motivations of volunteers: A functional approach. *Journal of Personality and Social Psychology*, *74*(6), 1516–1530. https://doi.org/10.1037//0022-3514.74.6.1516

Cohen, J. B. (1920). The scientific citizen. *Athenaeum*, 1830.

Eicken, H., Danielsen, F., Sam, J.-M., Fidel, M., Johnson, N., Poulsen, M. K., Lee, O. A., Spellman, K. V., Iversen, L., Pulsifer, P., & Enghoff, M. (2021). Connecting top-down and bottom-up approaches in environmental observing. *BioScience*, *71*(5), 467–483. https://doi.org/10.1093/biosci/biab018

Eurostat. (2018, April 4). *Work beats study for 25% of university dropouts*. https://ec.europa.eu/eurostat/web/products-eurostat-news/-/DDN-20180404-1

Follett, R., & Strezov, V. (2015). An analysis of citizen science-based research: Usage and publication patterns. *PLoS ONE*, *10*(11), Article e0143687. https://doi.org/10.1371/journal.pone.0143687

Gewin, V. (2020). Ways to look after yourself and others in 2021. *Nature*, *588*, 717–718. https://doi.org/10.1038/d41586-020-03558-w

Goddard, J., Hazelkorn, E., Kempton, L., & Vallance, P. (2016). *The civic university. The policy and leadership challenges*. Edward Elgar Publishing.

Haklay, M. (2013). Citizen science and volunteered geographic information: Overview and typology of participation. In S. Sui, S. Elwood, & M. Goodchild (Eds.), *Crowdsourcing geographic knowledge* (pp. 105–122). Springer. https://doi.org/10.1007/978-94-007-4587-2_7

Haklay, M. (2014, September 10). Citizen science in Oxford English Dictionary. *Po Ve Sham – Muki Haklay's personal blog*. https://povesham.wordpress.com/2014/09/10/citizen-science-in-oxford-english-dictionary/

Haklay, M., Dörler, D., Heigl, F., Manzoni, M., Hecker, S., & Vohland, K. (2021). What is citizen science? The challenges of definition. In K. Vohland, A. Land-Zandstra, L. Ceccaroni, R. Lemmens, J. Perelló, M. Ponti, R. Samson, & K. Wagenknecht (Eds.), *The science of citizen science* (pp. 13–35). Springer. https://doi.org/10.1007/978-3-030-58278-4_2

Jármai, E. M. (2018). Menedzserszerep-kihívások a felsőoktatásban – Az oktatói munka (de)motiváló tényezői. *Taylor*, *10*(1), 115–129. https://ojs.bibl.u-szeged.hu/index.php/taylor/article/view/13153

Magnussen, R. (2017). Involving lay people in research and professional development through gaming: A systematic mapping review. In *Proceedings of 11th European Conference on Games Based Learning (ECGBL 2017)* (pp. 394–401). Publisher Academic Conferences and Publishing International.

Maslach, C., & Jackson, S. E. (1982). Burnout in health professions. A social psychological analysis. In G. S. Sanders & J. Suls (Eds.), *Social psychology of health and illness* (pp. 227–247). Psychology Press.

Ostermann-Miyashita, E., Nadja, P., & König, H. (2021). Citizen science as a bottom-up approach to address human-wildlife conflicts: From theories and methods to practical implications. *Conservation Science and Practice*, *3*, Article 385. https://doi.org/10.1111/csp2.385

Parthenos. (2019, February 11). *Citizen science in the (digital) arts and humanities*. https://training.parthenos-project.eu/sample-page/citizen-science-in-the-digital-arts-and-humanities/

Sík, A., Bogdan, C., & Hargitai, E. (2021, September 13–17). *Transdisciplinary mentoring of bottom-up citizen science projects* [Conference presentation]. International Transdisciplinarity Conference, Zurich, Switzerland.

Site, L. (2017). Commentary: Surviving scientist burnout. *Physics Today*, *70*(9), 10–11. https://doi.org/10.1063/PT.3.3675

Somerwill, L., & Wehn, U. (2022) How to measure the impact of citizen science on environmental attitudes, behaviour and knowledge? A review of state-of-the-art approaches. *Environmental Sciences Europe*, *34*, Article 18. https://doi.org/10.1186/s12302-022-00596-1

UNESCO Institute for Statistics. (2019, June). Women in science. *Fact Sheet*, (55). http://uis.unesco.org/sites/default/files/documents/fs55-women-in-science-2019-en.pdf

UNESCO Recommendation on Open Science, November 2021, https://unesdoc.unesco.org/ark:/48223/pf0000379949.locale=en

Vohland K., Göbel, C., Balázs, B., Butkevičienė, E., Daskolia, M., Duží, B., Hecker, S., Manzoni, M., & Schade, S. (2021). Citizen science in Europe. In K. Vohland, A. Land-Zandstra, L. Ceccaroni, R. Lemmens, J. Perelló, M. Ponti, R. Samson, & K. Wagenknecht (Eds.), *The science of citizen science* (pp. 35–53). Springer. https://doi.org/10.1007/978-3-030-58278-4_3

Vohland, K., Land-Zandstra, A., Ceccaroni, L., Lemmens, R., Perelló, J., Ponti, M., Samson, R. & Wagenknecht, R. (2021). Editorial: The science of citizen science evolves. In K. Vohland, A. Land-Zandstra, L. Ceccaroni, R. Lemmens, J. Perelló, M. Ponti, R. Samson, & K. Wagenknecht (Eds.), *The science of citizen science* (pp. 1–12). Springer. https://doi.org/10.1007/978-3-030-58278-4_1

World Economic Forum. (2020, October). *Future of jobs report 2020*. https://www3.weforum.org/docs/WEF_Future_of_Jobs_2020.pdf

Biographical Notes

Evelin Gabriella Hargitai is a research and development expert, education expert, and trainer at the University of Pécs, Medical School, Institute of Transdisciplinary Discoveries.

ORCID: https://orcid.org/0000-0001-7251-3575
Email: hargitai.evelin@pte.hu
Address: H-7624 Pécs, Ifjúság útja 11

Attila Sik is a neuroscientist, head of the Institute of Transdisciplinary Discoveries, and has a master of business administration from the Warwick Business School (United Kingdom) in leadership and creativity.

ORCID: https://orcid.org/0000-0001-5572-2156
Email: sik.attila@pte.hu
Address: H-7624 Pécs, Ifjúság útja 11

Alexandra Samoczi is a research assistant at the Institute of Transdisciplinary Discoveries.

ORCID: https://orcid.org/0000-0002-0131-8606
Email: samoczi.alexandra@pte.hu
Address: H-7624 Pécs, Ifjúság útja 11

Milan Hathazi is a research assistant at the Institute of Transdisciplinary Discoveries. Graduated as a health developer from the Faculty of Health Sciences of the University of Pécs and obtained a qualification in mental hygiene at the Budapest University of Economics. Milan Hathazi is a micro-regional development expert.

ORCID: https://orcid.org/0000-0002-4964-8102

Email: hathazi.milan@pte.hu
Address: H-7624 Pécs, Ifjúság útja 11

Csaba Bogdán is a medical engineer and a doctoral candidate at the Doctoral School of Clinical Medicine at the University of Pécs.
ORCID: https://orcid.org/0000-0003-4469-3067
Email: csaba.bogdan@pte.hu
Address: H-7624 Pécs, Ifjúság útja 11

Submitted: 30/03/2022 | Accepted: 12/06/2022