Leveraging AI for Signal and Image Analysis in Medicine and Health

Marco Cafiso[1,2], Andrea Carboni[1], Claudia Caudai[1], Sara Colantonio[1], Francesco Conti[1,3], Mario D'Acunto[4], Said Daoudagh[1], Giulio Del Corso[1], Danila Germanese[1], Giacomo Ignesti[1,5], Gianmarco Lazzini[1], Giuseppe Riccardo Leone[1], Massimo Magrini[1], Davide Moroni[1], Francesca Pardini[1], Maria Antonietta Pascali[1,*], Paolo Paradisi[1] and Federico Volpini[1]

[1]*Signals and Images Lab, Istituto di Scienza e Tecnologie dell'Informazione "A. Faedo", ISTI-CNR, 56124, Pisa, IT*
[2]*Dipartimento di Fisica, Università di Pisa, 56127, Pisa, IT*
[3]*Research Centre Inria Sophia Antipolis - Méditerranée: Valbonne, Provence-Alpes-Côte d'Azur, FR*
[4]*Istituto di Biofisica, IBF-CNR, 56124, Pisa, IT*
[5]*Dipartimento di Informatica, Università di Pisa, 56127, Pisa, IT*

Abstract

The integration of artificial intelligence (AI) into the medical domain is driving innovation and progress in healthcare. This paper summarizes the research activities that a multidisciplinary research group within the Signals and Images Lab of the Institute of Information Science and Technologies of the National Research Council of Italy is carrying out to explore the great potential of AI in several applications, e.g., in the analysis of biomedical data, and in the development of tools for enhancing trustworthiness and reliability of AI based systems. From cancer diagnosis and grading, to the analysis of body physiological signals to improve the understanding of dance movement therapy as an approach to healthy aging, this work highlights the paradigm shift that AI has brought into medicine and healthcare.

Keywords

Thermal imaging, Raman spectroscopy, Physiological signals, Neuromotor rehabilitation, Dance movement therapy

1. Introduction

Advances in Artificial Intelligence are impacting many sectors of medicine and health; starting from supporting detection, segmentation, and classification in medical imaging to support diagnosis, AI improved also the analysis and understanding of healthcare data, e.g, improving the understanding of complex patterns of signals or contributing to cost-effective healthcare solutions, through more accurate diagnoses and personalized treatment plans.

However, it is important to look for an optimal trade-off between promoting the benefits of AI in clinical practice and everyday life, addressing issues about the trustworthiness of AI-based systems, such as robustness, transparency, explainability, reliability, and bias management.

This paper summarises the ongoing activities of a multidisciplinary research group within the Signals and Images Lab of the Institute of Information Science and Technologies of the National Research Council of Italy. The group aims to explore the potential applications of AI in promoting and supporting

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*Corresponding author.
maria.antonietta.pascali@isti.cnr.it (M. A. Pascali)
0009-0004-9519-1221 (M. Cafiso); 0000-0003-3227-3487 (A. Carboni); 0000-0002-1590-7890 (C. Caudai); 0000-0003-2022-0804 (S. Colantonio); 0000-0002-6385-6944 (F. Conti); 0000-0003-4233-1943 (M. D'Acunto); 0000-0002-3073-6217 (S. Daoudagh); 0000-0003-4604-2006 (G. D. Corso); 0000-0002-7814-5280 (D. Germanese); 0000-0003-2389-3086 (G. Ignesti); 0000-0001-5539-6717 (G. Lazzini); 0000-0002-7441-8528 (G. R. Leone); 0000-0002-0559-0607 (M. Magrini); 0000-0002-5175-5126 (D. Moroni); 0000-0002-4324-2718 (F. Pardini); 0000-0001-7742-8126 (M. A. Pascali); 0000-0002-1036-4583 (P. Paradisi); 0009-0008-9734-9036 (F. Volpini)

health and well-being, while also addressing the challenges related to robustness, uncertainty, privacy, security, and compliance with ethical standards and existing regulations.

2. AI in Raman Spectroscopy

Raman spectroscopy (RS) is a label-free molecular vibrational spectroscopy technique that is able to identify the molecular fingerprint of various samples making use of the inelastic scattering of monochromatic light. Because of its advantages of non-destructive and accurate detection, RS is gaining more and more success in several the health domain, e.g., to distinguish between health or benign and malignant tissues, to classify the cancer subtype, and to support the anatomopathologist, operating either in vivo or in vitro. Recent advances show that best results are achieved through the combination of data pre- and post-processing methods with current methods of Artificial Intelligence (AI), i.e., Machine Learning (ML), Deep Learning (DL), and Topological Machine Learning (TML), as pointed out in [1].In [2], we adopted Machine Learning (ML) algorithms to interpret Raman spectra obtained with a Confocal Raman Microscope to diagnose melanoma from histologic sections of solid biopsies. Notably, the accuracy of the binary classification Compound Naevus (CN) vs. Primary Cutaneous Melanoma (PCM) achieved values of $\sim$ 96% using Principal Component Analysis (PCA) and Linear Discriminant Analysis (LDA), and $\sim$ 97% using a Random Forest Classifier (RFC).

In a more recent work [3], we discuss how to improve the diagnostic speed leveraging the dimensionality reduction, in the very challenging task of diagnosing solid biopsies of Pancreatic Ductal Adenocarcinoma (PDAC) from Normal pancreas (N) and chronic pancreatitis (P). We compared the traditional PCA with a conceptually simpler approach, based on the selection of sub-bands, aka SPSEL and tested the performance of three ML classifiers, i.e., LDA, Gaussian Naive Bayes (GNB), and a RFC. Despite the best performances associated with PCA and SPSEL being similar ($\sim$ 96% for RFC), SPSEL offered the additional advantage of providing indications about the minimum spectral range required to maximize the classification accuracy, with relevant consequences in terms of signal acquisition time. Finally, SPSEL allowed for the detection of spectral sub-bands associated with the best classification performances which, by definition, are representative of cancer molecular biomarkers.

In the same case study, the topological pipeline presented in [4] achieved an accuracy of 88% for the binary classification of cancer vs. no cancer and an accuracy of 82% for the 3-class task (PDAC vs. P vs. N), computed following a cross-validation scheme with patient stratification. Our previous research includes applications of RS+TML to cancer detection and grading from RS of sample tissue for chondrogenic cancer [5], as well as from other biological sample, i.e., the cerebrospinal fluid for detecting the Alzheimer's disease, achieving a high classification accuracy of 86%, computed following a leave-one-out validation scheme [6]. This last methodology opens the way to improving and/or confirming the knowledge about the precise molecular events and biological pathways of the case study considered, e.g. by identifying the bands of the Raman spectrum relevant for the Alzheimer's disease detection. Future efforts will be focused on the assessment of the "band importance" and fall within the study of novel approaches to achieve explainability, a key point to increase end-user's acceptance and awareness of AI-based system.

3. AI in Body Motion and Physiological Signals

Human physiological, behavioral, and social data constitute a tangible manifestation of human complexity, which can be crucial for understanding the associated benefits on both individual and social well-being, in particular when exploited in the realm of AI.

3.1. Dance Movement Therapy

Dance Movement Therapy (DMT) is a complementary (psycho-)therapy approach that uses dance and movement to support physical, emotional, and cognitive healing. In recent years, the integration of AI in DMT has become a promising tool for enhancing therapeutic practices, particularly in the context of older adults. Our current research project, DMT@AA@THE, is part of the Active Aging (AA) subproject within the broader PNRR Tuscany Health Ecosystem (THE), which focuses on DMT for active aging, with participants over 65. It aims to assess both movement and physiological signals by employing AI technologies [7]. We are currently concluding a two-cycle experimental study involving 13 participants in the first cycle and 14 in the second, with each cycle consisting of 8 sessions held once a week. The study explores how DMT, enhanced with AI-driven motion and physiological analysis, can support healthier aging processes and improve physical and mental well-being.

Human pose estimation models and wearable sensors capture and analyze body movements during DMT sessions. These technologies enable precise tracking of movement patterns, range of motion, and overall body posture. The collected data allows for an objective assessment of participants' progress, aiming at revealing critical improvements for aging populations in areas such as flexibility, balance, and motor coordination.

Currently, AI is primarily used for body motion analysis [7]. The DMT Pose Estimation GUI is designed to facilitate seamless human pose estimation on videos recorded during DMT sessions. In contrast, physiological signals, such as ECG, breathing rate, and galvanic skin response (GSR), are analyzed using more classical and benchmark algorithms. Nevertheless, multimodal AI approaches represent a promising future advancement: combining different data types, such as images and physiological signals, could provide deeper insights into participants' emotional and physical states during DMT sessions [8]. The integration of AI in our DMT protocol could help not only to track individual improvements and to enable more personalized therapeutic interventions, but also to assess group dynamics which is important for understanding the social and emotional benefits of DMT. This is particularly relevant in an aging population, where social interaction and emotional support are key factors in overall well-being [9].

3.2. Bio-Inspired Learning

The human being is, on one hand, a source of valuable data for training AI algorithms and, on the other hand, a source of inspiration for developing solutions for AI models, in particular bio-inspired neural networks. By studying human complexity, researchers can create more sophisticated models that mimic these natural systems. Researchers have consistently used the human brain as their primary inspiration for creating learning algorithms since the earliest beginnings of AI development. Though the basic component in both standard Artificial Neural Networks (ANNs) and Deep Artificial Neural Networks (DANNs) is termed a "neuron", this computational unit bears little resemblance to the functioning of biological neurons. Spiking Neural Networks (SNNs) represent a specialized category of ANNs that more accurately replicate brain functionality. In these models, neurons interact via discrete spikes rather than continuous signals, making traditional ANN learning techniques ineffective for their training. Their potential regards not only the energy efficiency but also the sensibility of changes in time series such as human physiological signals. In particular, they are characterized by nonlinear dynamical models that can be studied through the lens of the complex system theory [10]. New research demonstrates connections between the spatial topology in basic Spiking Neural Networks and measurements coming from Temporal Complexity theory [11]. Specifically, the researchers discovered that within their examined network, varying structural configurations appear to generate comparable dynamic patterns across different parameter ranges, with Temporal Complexity measurements remaining consistent across distinct dynamic behaviours.

3.3. Exergames and AI in Neuromotor Rehabilitation

Neuroplasticity, the brain's capability to alter its structure and function in response to neuronal activity, such as that elicited by somatosensory stimuli, forms the physiological basis of neurorehabilitation and the associated processes of learning and motor control. Within this framework, a specific research direction focuses on enhancing neuromotor rehabilitation through the development of innovative exergames that incorporate AI-driven methodologies and novel sensor technologies. Our prior research [12, 13] has presented contributions involving a passive robotic aid integrated with exergames for upper limb post-stroke recovery, which demonstrated functional improvements and patient engagement. A current project, *Fingertask*, involves an exergame designed for monitoring fine motor skills of the hand. This system has been implemented as a completely touchless interface, utilizing a contactless hand gesture controller, specifically Leap Motion. Fingertask is currently undergoing testing and validation in various contexts. This includes a trial within the Tuscany Health Ecosystem projects, in conjunction with an Assisted Physical Activity (APA) program. This program is being monitored using a multidisciplinary and multisensor approach, with results anticipated by the end of 2025.

4. AI Trustworthiness in Health and Medicine

AI trustworthiness, along with its related aspects such as reliability and robustness, plays a major role in modern artificial intelligence methods, particularly in critical domains.

The lack of trustworthiness of AI is probably the main reason whythe deployment and adoption of AI technologies remains limited in clinical practice [14]. We contributed to [15], in which authors propose a general framework, i.e., the FUTURE-AI framework, which provides guidance to guarantee trustworthiness (principles—fairness, universality, traceability, usability, robustness, and explainability) in the healthcare domain, along with a set of tools and recommendations covering the entire lifecycle of healthcare AI, from design, development, and validation to regulation, deployment, and monitoring.

In order to improve trustworthiness and reliability of AI methods, Bayesian learning and probabilistic modeling offer viable tools, e.g., to prevent overconfident predictions or to teach models how to identify out-of-distribution (OOD) and anomalous cases (*learning-to-defer*). A concise and complete review which combines the classical mathematical formalization of uncertainty with the modern theory of Bayesian deep learning is [16], where a formal definition of *Epistemic* and *Aleatoric uncertainties* is provided, as well as a selection of optimal techniques. The development of novel uncertainty-aware techniques for medical image analysis is a challenging topic that requires careful testing before full deployment; to this aim, we introduced a synthetic shape generator (NADA) and created an open-access collection of images explicitly designed to test and benchmark probabilistic methodologies [17].

An interesting medical application is represented by the use of probabilistic Networks for the analysis of ultra-sound images for grading Fatty Liver Content (FLC) in Metabolic Dysfunction Associated Steatotic Liver Disease (MASLD) patients [18]. The use of probabilistic approaches, such as Monte Dropout and Bayesian Neural Networks, allows the introduction of a category of ”non-confident” outputs that in the medical field can be highly useful, increasing the accuracy on the confident classes.

A more intrusive approach, based on the ensembling of several models (Deep Dummy Ensemble), allows for leveraging the capabilities of uncertainty-aware methods across different application domains, such as the prediction of side effects after treatment for prostate cancer [19], thus demonstrating the flexibility of such methods across the entire spectrum of medical applications.

5. AI for the Newborn

From early detection of congenital conditions to real-time monitoring of vital signs, there is a growing body of research focused on the use of artificial intelligence technologies to support clinicians in providing more personalized, timely, and effective care for newborns [20].

In collaboration with the NINA laboratory (https://www.centronina.it/en/) and the NICU of Santa Chiara Hospital in Pisa, a study was conducted focusing on monitoring neonatal thermoregulation. Thermoregulation is a critical aspect of neonatal care, as both preterm and term infants have immature thermal control mechanisms in the immediate postnatal period. This study proposed a noninvasive integrated system to monitor temperature changes during the first hours of life, with the aim (as part of a larger study whose protocol is under review) of assessing neonatal well-being through thermal pattern analysis and investigating the effects of skin-to-skin contact (SSC) on thermal stabilization. The system consists of an RGB camera, thermal and environmental sensors, and a Raspberry Pi managed by custom Python software. After validation in a controlled environment, the data was collected in the hospital using a neonatal mannequinthat replicates the thermal behaviour of a newborn. RGB images were used exclusively for the extraction of anatomical landmarks, which facilitated the alignment and processing of thermal images while ensuring privacy. Adaptive regions of interest (ROIs) were generated from skeletal landmarks to extract thermal histograms. In the frames where the background was detected, a CNN-based segmenter (FastSAM) was activated to isolate the relevant anatomical areas. A radiomics-inspired approach was then used to extract thermal features, including median and interquartile range. Global features were also defined to relate different regions of the body, supporting a comprehensive evaluation of thermal patterns.

6. Conclusions

AI has a big potential to improve care and health systems, showing a large span of applications: diagnostic tasks, facing also very important issues, like uncertainty quantification and explainability of predictions, supporting the use of thermal imaging for improving the comprehension of the newborn physiology, and also for improving the understanding of physiological signals in adults for therapeutic and rehabilitation purposes (e.g., dance movement therapy and exergames). Also, future research should involve healthcare professionals and caregivers as designers and users, comply with health-related regulations, improve transparency and privacy, enhancing all the trustworthiness dimensions to support the user acceptance of AI-based tools and, finally, to promote the diffusion of such methods in clinical practice and in everyday life.

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Declaration on Generative AI

During the preparation of this work, the authors did not use any generative AI.

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