Óbuda University

PhD Thesis Summary

Development of machine learning solutions for modeling and automation of processes

by
Lehel Dénes-Fazakas

Supervisors:
Dr. habil György Eigner
Prof. Dr. habil László Szilágyi

Doctoral School of Applied Informatics and Applied Mathematics

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Contents

List of abbreviations

AI	Artificial Intelligence
CGMS	Continuous Glucose Monitoring System
CNN	Convolutional neural network
CT	Computed Tomography
ELU	Exponential Linear Unit
MRI	Magnetic Resonance Imaging
OCT	Optical Coherence Tomography
PET	Positron Emission Tomography
PPO	Proximal Policy Optimization
RL	Reinforcement learning
RNN	Recurrent Neural Network
TIR	Time In Range

1. Motivation

Artificial intelligence (AI) is at the heart of modern technological advancements, and its application in medicine has become increasingly prominent in recent years [R1, R2]. AI-based solutions now assist in a wide range of clinical activities, including process automation, disease prediction, personalized treatment planning, and medical diagnostics. These developments are helping to reshape healthcare, making it more predictive, personalized, and efficient.

Despite the breadth of AI's potential, my research focuses on two critical domains where these technologies can provide substantial societal impact: diabetes mellitus and medical image processing. These areas were chosen due to their growing prevalence, high data availability, and the direct benefit they offer to both patients and healthcare professionals.

The first research direction addresses diabetes mellitus, a chronic metabolic disorder affecting millions globally [R3, R4, R5]. Within this domain, my work aims to enhance the functionality of artificial pancreas systems through three key contributions: physical activity recognition using wearable sensors, gesture-based food intake detection, and intelligent insulin regulation using reinforcement learning. Each of these components is critical to managing diabetes effectively. For instance, undetected physical activity may mimic the effect of insulin and lead to hypoglycemia, while unlogged food intake can result in unexplained variations in blood glucose, complicating therapeutic decisions. Moreover, the manual process of determining optimal insulin dosing regimens is time-consuming and prone to suboptimal outcomes. By applying reinforcement learning, insulin delivery can be personalized, continuously adapted, and optimized in real-time based on a patient's glucose dynamics. Through the integration of AI-driven solutions for activity monitoring, meal detection, and autonomous insulin regulation, my research contributes to safer and more efficient diabetes care. These tools aim to automate routine tasks, reduce the cognitive burden on patients, and provide physicians with more accurate and continuous data, ultimately supporting better clinical outcomes.

The second major area of research lies in the domain of medical image analysis, particularly magnetic resonance imaging (MRI). Modern imaging modalities such as MRI, PET, CT, and OCT offer unique perspectives on anatomical and physiological processes [R6]. However, accurate interpretation of these images requires expert knowledge and can be time-consuming. My research contributes to this field by developing deep learning methods for brain MRI segmentation and tumor classification. These methods are applied to both neonatal and adult MRI datasets. For neonates, the segmentation of brain tissues such as gray matter, white matter, and cerebrospinal fluid is a crucial task for early detection of developmental abnormalities. For adult patients, accurate classification of brain tumors into categories such as glioma, meningioma, or pituitary tumor supports faster and more precise diagnostics, which is essential for treatment planning.

Overall, my research aims to bridge the gap between AI advancements and clinical utility. The developed models are designed with real-world applications in mind—either to be embedded in wearable devices like smartwatches or deployed as clinical decision support systems. These contributions, while technically grounded, are always evaluated through the lens of practical benefit to patients and clinicians.

2. Aims of the research

The main goal of my PhD research was to design artificial intelligence (AI) models that are practical, robust, and usable by both healthcare professionals and patients. These AI models aim to assist doctors in diagnostic and therapeutic tasks, while also supporting patients in their daily self-management by automating routine, administrative, or health-related functions.

To achieve this, I focused on two distinct medical fields—diabetes mellitus and medical image analysis—where AI can have a tangible impact. Each of these domains involves complex, high-frequency data and benefits significantly from machine learning-based optimization, prediction, and pattern recognition.

AI Applications in Diabetes Care

Diabetes mellitus remains a pressing global health challenge, and recent developments in wearable technology and continuous monitoring have opened new avenues for intelligent systems. My research in this domain was structured around three central objectives:

1. Physical Activity Detection

For patients with Type 1 diabetes, artificial pancreas systems have been developed to automate insulin delivery [R7]. These systems typically consist of three components: a Continuous Glucose Monitoring System (CGMS), an insulin pump, and a control algorithm. However, a major limitation is their inability to detect physical activity, which can significantly reduce blood glucose levels in a manner similar to insulin. This leads to dangerous conditions such as hypoglycemia, which can result in unconsciousness or even death if not properly managed.

To address this, I developed AI-based systems capable of detecting physical activity using data from wearable sensors. Importantly, I focused on minimizing sensor dependency to reduce patient burden, ensuring that the models remain practical for real-world deployment. The developed methods utilize both traditional machine learning algorithms and more advanced recurrent neural networks, achieving high accuracy while requiring minimal data preprocessing.

2. Insulin Regulation through Reinforcement Learning

The second area of research focused on optimizing insulin dosing using reinforcement learning (RL) techniques [R8]. Traditionally, the setup of insulin dosing regimens is done manually by physicians through a time-consuming trial-and-error process, which may not yield optimal results.

My objective was to develop an adaptive RL-based controller that could learn from a patient's historical glucose data and dynamically regulate insulin delivery. This patient-specific model can be integrated directly into insulin pumps, allowing for continuous fine-tuning and adaptation as the patient's condition changes over time. Among the algorithms tested, the Proximal Policy Optimization (PPO) method yielded the most promising results for blood glucose control.

3. Gesture-Based Meal Detection

The third contribution within the diabetes domain involved gesture recognition, specifically for detecting food intake using hand motion data [R9]. Many patients fail to accurately log their carbohydrate intake, which affects the reliability of treatment and monitoring. I developed personalized models based on accelerometer data that could detect eating gestures with high precision.

This system reduces the need for manual food logging and supports the automation of dietary tracking. In clinical settings, it enables physicians to better correlate glucose fluctuations with unrecorded meals, thereby improving overall treatment accuracy.

AI in Medical Image Processing

The second major focus of my research involved applying deep learning methods to medical image processing, with the aim of improving diagnostic precision and reducing the manual workload of radiologists and clinicians.

1. Infant Brain Tissue Segmentation

One area of study was the segmentation of brain tissues in MRI scans of 6-month-old infants [R10]. The goal was to accurately differentiate between white matter, gray matter, and cerebrospinal fluid—an inherently difficult task due to the overlapping intensities in infant brain development.

By developing modified U-Net architectures, including 2D, 3D, and (2+1)D convolutional variants, I achieved high segmentation accuracy. The resulting models could be used as early diagnostic tools to assess the likelihood of neurodevelopmental disorders in infants, which is crucial for timely intervention.

2. Brain Tumor Classification

The final component of my thesis addressed tumor classification in adult brain MRIs[R11]. I developed deep learning models capable of distinguishing between three common tumor types: glioma, meningioma, and pituitary tumors. These models provide essential support in the diagnostic pipeline by offering fast, consistent, and reliable tumor categorization.

Additionally, I proposed a hybrid model that performs both segmentation and classification simultaneously, effectively combining spatial and diagnostic understanding into a single architecture. This dual-purpose model increases the efficiency of image analysis and is suitable for integration into clinical decision support systems.

Overall Contribution

In summary, my research contributes AI-driven solutions to two critical areas of healthcare. The developed systems not only show strong experimental results but are also designed with real-world usability in mind. Whether embedded into wearables like smartwatches or deployed via cloud-based medical platforms, these models aim to make healthcare more intelligent, automated, and personalized.

3. Materials and methods

Thesis group 1:

- Physical activity detection
  - Physical activity detection using machine learning algorithms
  - Physical activity detection with recurrent networks
- Gesture detection
  - Gesture detection with machine learning algorithms
  - Gesture detection with recurrent networks
- Insulin regulation based on reinforcement learning
  - Investigation of reinforcement learning algorithms
  - Examination of hyperparameters
  - Reward function testing

Thesis group 2:

- Segmentation of infant brain MRI images
  - U-network analysis
  - 3-dimensional U-net analysis
  - Transformed cost function test
  - (2+1)D convolutional U-net investigation
- Classification of brain MRI tumor images
  - VGG-like network analysis
  - Hyperparameter calibrations
  - Fusion of U-net and CNN network with L-net

4. New scientific results

4.1 Diabetes-related research

Thesis group 1: Diabetes research

Thesis I.1
I developed methods to detect physical activity of diabetes patients using artificial intelligence methods.

Thesis I.1.1
I have developed different methods using conservative artificial intelligence methodologies to detect physical activity in case of synthetic patient data. The results shown that recognition of physical activity in this scenario is possible using only blood glucose level.

Thesis I.1.2
I have developed methods to recognize physical activity in case of real patient data using artificial intelligence solutions. I have compared the results to the results of Thesis I.1.1 and it turned out that in case of real data the usage of only the blood glucose level is not sufficient. I successfully extended the physical activity detection solutions to consider heart rate data as well. Combining blood glucose and heart rate data provided satisfactory rate of recognition of physical activity.

Thesis I.1.3
I have demonstrated that using recurrent neural networks can produce much better results than simple machine learning algorithms to detect physical activity while they consider the blood glucose level data, heart rate data, and other derived modalities. I have proved that these networks do not require any preprocessing.

Thesis I.2
I have developed an artificial intelligence-based solution that can detect eating gestures using only accelerometer data. This solution is useful to determine when the patient is taking in carbohydrates, which knowledge is essential for any dietary decision support system or blood glucose control systems.

Thesis I.2.1
I have demonstrated that it is possible to create a personalised gesture detection model for the patients based on the given patient's dataset. According to the tests, this approach is sufficient to provide sophisticated results in eating gesture recognition for the given patient.

Thesis I.2.2
I have demonstrated that it is sufficient to use only one day of data to create an artificial intelligence-based method that can detect eating gestures with accurate results.

Thesis I.3
I have developed reinforcement learning-based blood glucose control methods for diabetes patients. The developed solutions use only blood glucose values from continuous blood glucose sensors with satisfactory results according to the defined metrics.

Thesis I.3.1
In experiments using several models, I have demonstrated that the PPO model performs best for the blood glucose regulation problem and administering the best working insulin schemes to regulate blood glucose level. I have demonstrated even if the model was trained only on a limited time horizon in terms of data, it successfully extrapolates the control to a larger time horizon if the training data covered a good representation of blood glucose data under regular conditions.

Thesis I.3.2
I demonstrated that the usage of the mixture of bump reward function and ELU activation function in the last layer of neural networks provides the best results for blood glucose regulation. I also proved that deeper networks performed better in this case without overfitting.

Publications relevant to the theses: [C1, C2, C3, C4, J1, C5, J2, C6, J3, J4].

This research is divided into several subtopics, although it originates from a unified research effort. The overall focus lies in applying artificial intelligence (AI) to improve diabetes management. Within this broader theme, I concentrated on three key areas: physical activity detection, gesture-based meal detection, and insulin regulation using AI-based models.

The first topic, and the one I spent the most time on, was the detection of physical activity in diabetes patients. This is reflected in the volume of related publications, including two journal articles [J1, J2] and a conference paper [C5]. Through this work, I demonstrated that it is feasible to detect physical activity using blood glucose and heart rate data. Moreover, I showed that recurrent neural networks (RNNs) significantly improve recognition accuracy without the need for complex preprocessing [J2]. Nevertheless, I also proved that even basic machine learning algorithms can yield acceptable results [J1]. Additionally, I validated the models through simulations and real-world datasets, showing that simulator-based experiments still offer valuable insight and do not mask real-world behavior [C5].

The second research direction focused on gesture detection, particularly the detection of food intake using inertial measurement data. I initially developed a simple machine learning model [C4], which achieved approximately 90% accuracy in meal detection using accelerometer data. To improve the robustness of this approach, I further evaluated the method on a published dataset [J3], where I applied a recurrent neural network architecture. The resulting models achieved around 98% accuracy across over 300 patients, supporting the feasibility of building persistent, personalized models for meal detection. Each model was trained individually on a single day of patient data and still performed remarkably well. While more data could help refine the models further, even limited training data proved sufficient to establish reliable gesture-based meal detection.

The third and final focus area involved insulin regulation using reinforcement learning. This work aimed to replace traditional medical protocols with intelligent, adaptive AI models. My first study [C3] evaluated various reinforcement learning algorithms for blood glucose control, showing that the Proximal Policy Optimization (PPO) algorithm delivered the best results. While testing over extended time periods revealed some performance degradation compared to the training phase, the models remained stable as long as the training data included representative glucose dynamics.

In a follow-up study [C2], I explored different reward functions for training the RL controller and found that the bump reward function consistently outperformed others, including cosine-based alternatives. Additionally, I showed that allowing the simulation to run continuously throughout the entire training period yielded better results than stopping it intermittently.

Further optimization [C1] involved tuning hyperparameters of the PPO model. These experiments revealed that while neuron count had a limited effect on performance, using the Exponential Linear Unit (ELU) activation function was critical to achieving a Time-in-Range (TIR) metric above 70%. Moreover, deeper network architectures enhanced performance without significant risk of overfitting.

In my final study [J4], I consolidated earlier findings and developed a large-scale patient-specific model using ELU activation. For the first time, I used distinct architectures for the value and policy networks and trained the model over a longer period. The resulting system showed excellent performance for patients weighing over 70 kg. However, performance was suboptimal for patients below this weight threshold, suggesting the need for personalized models based on patient-specific attributes. These findings also highlighted that a single day of training is insufficient for optimal performance and emphasized the importance of extended simulation-based learning.

In summary, I successfully addressed all three subtopics within my PhD research. Each result was supported by peer-reviewed publications and used iteratively to inform further development. The methods proposed throughout this work offer practical AI-based solutions that can significantly improve daily life for patients with diabetes. These solutions can be implemented on wearable devices such as smartwatches or smartphones, enabling seamless integration into existing diabetes management workflows. Collectively, my thesis contributes tools for automatic meal detection, continuous insulin adjustment, and physical activity recognition—each of which addresses critical gaps in current diabetes care.

4.2 Processing MRI images

Thesis group II: Researches focused on the advanced processing techniques applied to MRI imaging data

Thesis II.1
I developed an artificial intelligence-based solution for the pixel-level segmentation of infant brain tissues from MRI images. My solution can greatly help the medical staff in the detection of abnormal development of the brain.

Thesis II.1.1
I have shown that it is not mandatory to follow the traditional U-net architecture. My experiments revealed that decreasing the filter numbers in consecutive encoding blocks and increasing them in consecutive decoding blocks can also provide fine segmentation.

Thesis II.1.2
I have shown that using non-traditional cost functions in training can be beneficial. Using a Dice similarity score-based cost function gives much better results than using a traditional categorical cross-entropy function.

Thesis II.1.3
I have shown that it is worthwhile to deploy (2+1)D convolution, frequently used in video processing, in the segmentation problem. Consecutive slices of a volumetric MRI record correlate as much as consecutive frames of a video.

Thesis II.2
I have developed solutions that classify brain MRI tumor images more accurately than state-of-the-art models. In addition, I have developed a solution that can classify and segment the tumor simultaneously.

Thesis II.2.1
I have shown that reducing image size to a certain extent improves the classification accuracy of brain tumor MRI images. Furthermore, I have shown that a better training strategy is to save the model continuously when the accuracy on the validation dataset increases during training. I also proved that a large network size is not needed for all problems. In particular, if the problem is specific, smaller architectures may solve the problem better.

Thesis II.2.2
I proved the theory that if you train a network on two problems simultaneously, you can get better results than if you train on only one problem at a time. In addition, I have created a network model that can segment and classify accurately at the same time, when all data is available.

Publications relevant to the theses: [C7, C8, J5, J6, J7].

This research section contains only two subsections, as I conducted two distinct studies in the field of medical image analysis. The first of these focused on infant brain segmentation from MRI images. The goal was to segment the brain tissues of 6-month-old infants, specifically the white matter, gray matter, and cerebrospinal fluid.

For this task, I proposed a modified U-Net architecture, as described in my first article [C8]. This modification deviated from the traditional U-Net design by decreasing the number of filters in successive encoding layers and increasing them in the decoding layers, contrary to the conventional approach. In my second article [J5], I evaluated a larger two-dimensional U-Net and also experimented with a three-dimensional U-Net. As detailed in the paper, the 3D U-Net achieved comparable segmentation performance while utilizing fewer filters than its 2D counterpart.

In this study, I also introduced a novel cost function, moving away from the standard categorical cross-entropy. Instead, I combined it with the Dice similarity coefficient to create a hybrid loss function. Specifically, I calculated the Dice score for the four classes, subtracted it from 1, multiplied the result by 0.5, and added it to the categorical cross-entropy (also scaled by 0.5). This blended cost function proved effective and led to improved segmentation outcomes.

In a third publication [J7], I implemented a novel approach by applying (2+1)D convolutions—commonly used in video classification—to the segmentation of volumetric MRI data. Since consecutive slices of a 3D MRI can be considered analogous to video frames, this technique captured inter-slice spatial relationships more effectively, and achieved the best segmentation results among all the tested architectures.

The second research direction focused on brain tumor classification. Unlike standard approaches that detect the presence of a tumor, my goal was to classify the type of tumor - distinguishing between glioma, meningioma, and pituitary tumors. In my first paper [C7], I compared a lightweight convolutional neural network (CNN) that I developed with several state-of-the-art models. I tested different training strategies—one based on minimizing the loss function, and another on maximizing validation accuracy. The experiments revealed that selecting models based on maximum validation accuracy yielded superior performance.

Additionally, I found that reducing the input image resolution from the original 512×512 to 256×256 improved both training efficiency and final performance. Other important findings included the necessity of using dropout layers for regularization, and that a kernel size of 9×9 did not provide better results. Interestingly, variations in the number of neurons in the dense layers had minimal effect on overall model performance. Despite its simplicity, my model outperformed larger, more complex architectures, suggesting that smaller, well-tuned networks may be better suited for certain domain-specific tasks.

In the following study [J6], I explored the idea of fusing segmentation and classification into a single model. Leveraging my earlier work with U-Net and CNN architectures, I connected the final convolutional layers of the U-Net (prior to the segmentation output) to a separate classification head derived from my earlier CNN model. Since the tumor segmentation masks were available, this allowed me to train the model for both tasks simultaneously. The final experiments—performed with a 128×128 input resolution—confirmed previous findings and yielded excellent performance. Notably, the joint segmentation-classification model achieved an F1-score exceeding 0.99, improving upon the 0.982 score from the earlier classification-only model.

Overall, my work in medical image analysis has been centered around MRI data. In both areas—infant brain segmentation and brain tumor classification—I succeeded in developing models that can accurately perform their respective tasks. Furthermore, the fusion of these two functionalities into a single, multitask model demonstrates the feasibility of efficient, dual-purpose deep learning solutions. These models can be readily deployed in clinical environments, either through cloud-based systems or on local computing platforms, thereby streamlining diagnostic workflows and supporting medical professionals in their decision-making processes.

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