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INTEGRATION OF DIGITAL TWIN IN GLAUCOMA IDENTIFICATION AND MONITORING – AN ADVANCED PERSPECTIVE IN OPHTHALMOLOGIC DIAGNOSIS

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Digital Twins are becoming part of complex systems in various domains such as: manufacturing, medicine, smart cities, and energy production. This paper addresses the application of Digital Twin in medicine, particularly in ophthalmology. Digital Twins can be developed in relation to organs, systems and even the entire human body and concepts from system of systems theory can be applied. The focus is on training a convolutional neural network based on a multi-modal dataset of longitudinal follow-up visual field and fundus images for glaucoma management.

Keywords: Digital Twin, Medical Digital Twin, GRAPE dataset, ophthalmologic diagnosis, glaucoma

1. Introduction

The rapid development of technologies and the use of new techniques, tools, and machines significantly contribute to progress in various fields such as production, agriculture, the educational system, healthcare, and the enumeration can continue [1]. Thus, the foundations are laid for innovative systems in various domains, which lead to the emergence of tangible benefits in people's lives.

One of the innovative technologies that offers opportunities for improving processes and decision-making in various fields through real-time monitoring, simulation, and analysis of the behaviors of physical entities is the Digital Twin. The medical field is one of the areas of interest where ICT (Information and communication technology) is becoming increasingly utilized. Thus, the Digital

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Twin can contribute to enhancing the safety and efficiency of healthcare, prioritizing confidentiality, security, and authorized access to the medical data that will be used. In this context, a Digital Twin represents a physical entity digital model and its associated behavior, realized through a data connection which enables the mirroring of the physical entity into a virtual one. During this conversion, between the two entities an important synchronization level should be maintained. Still, it is important to mention that the Digital Twin concept differs from the simulation one because it uses and process real time data, directly achieved through the communication between physical and virtual system.

The interest in conducting research on the applicability of Digital Twin in the medical field is continuously growing. Thus, in [2] and [3], aspects are highlighted that lead to the idea that one of the most critical sectors to benefit from Digital Twins is the healthcare industry. By using wearable devices and sensors, data about the patient's health can be collected, and by integrating them into the Digital Twin model, the patient's health status can be monitored in real time. This allows the physicians the possibility to prescribe predictive treatments, and, after that, them can be adjusted. As a result of real-time data received from the patient and recognizing situations where the patient needs medical intervention, by using DTs, Ambulances can reach the patient’s location, which decreases the severe complications risks. In [4], some ethical aspects related to the use of DTs in this field were presented, which may lead to discrimination and segmentation through the use of data that highlights lifestyle.

Digital Twins can be used to realize telemedicine interventions, such as remote surgery or in other emergency situations, as presented in [5]. With the help of Digital Twins, simulations regarding the performance of surgeries could be conducted. Thus, the Digital Twin can be considered a supportive element for the specialist doctor, providing them with a comprehensive view regarding the simulation of the patient's behavior after surgery and postoperative reactions. The development of a secure, reliable link or network which provide access to data provided by Digital Twins is an increased necessity for precise diagnosis [6].

The Digital Twin application in healthcare consists of the following main phases:

- real – time data transmission between the physical object and its virtual counterpart.
- execution of the simulated digital models, followed including their testing and validation.
- constantly and iteratively adjusting and fine tuning the models, to optimize digital model functionality.
- with the aid of the physical entity virtual counterpart behavior, model output data, signifying in fact the diagnosis and treatment results are communicated to the patient for the diagnosis results.

Finally, a patient digital model is intended to be obtained, followed by lifelong updates according to physical examinations, scanning, measurements. At the same time, the personalized patient model takes account of her / his genetic and behavioral data.

In our paper, a Digital Twin application in ophthalmology, more exactly for glaucoma diagnosis and treatment is presented. The paper is organized as follows: Section 2 presents several aspects related to the use of DTs in the context of Personalized Medicine and Systems Medicine. Digital Twin applications for ophthalmology is highlighted in 2.1. and in 2.2, an architectural framework for glaucoma detection and personalized treatment allocation is presented. Section 3 contains the Materials and Methods while the Sections 4 and 5 are reserved for Experimental results and the discussions.

2. Digital Twin for Personalized Medicine and Systems Medicine

Unlike other fields of application such as manufacturing, energy production, and smart cities, the application of Digital Twin in medicine involves forming a complex picture of the entire organism seen as a system of systems, where each represents an organ. The following sections will present several aspects related to the implementation of a Digital Twin associated with an organ, the Digital Twin associated with a pathology, and the Digital Twin associated with the entire human body. Following a study on the applicability of the Digital Twin in various segments of medicine, no significant results were found in the field of ophthalmology. Therefore, our focus is on the application of the Digital Twin in ophthalmology, especially for identifying glaucoma and providing personalized treatments.

According to the World Health Organization [7], the number of people with visual impairments has significantly increased in recent years, reaching at least 2.2 billion cases globally. The main identified cases of visual impairments include refractive errors, cataracts, glaucoma, diabetic retinopathy, and age-related macular degeneration. However, statistical analysis has shown that approximately half of these cases of visual impairments could have been prevented. Therefore, with the help of the Digital Twin, we aim to provide medical professionals with an integrative approach to identifying predispositions to certain eye pathologies while also outlining an overview of the disease progression stages.

2.1. Perspectives for Digital Twin in the medical field

In the field of medicine, the construction of a Digital Twin emphasizes the integration and processing of information from various sources such as medical databases, medical consultations, and medical imaging, with the purpose of identifying various pathologies and simulating their evolution based on various parameters. Another functionality provided by the Digital Twin is the provision of personalized treatment and monitoring of the patient's behavior towards the proposed medication, with the progression of the pathology being monitored by the specialist physician who influences the outcomes through a feedback system. The integration of this feedback system leads to continuous training of the model and improvement of the results provided by the Digital Twin. Thus, there are several approaches to constructing a Digital Twin, whether it is focused on an organ, a pathology, or the entire human body, aspects that will be highlighted in this section.

- *Digital Twin associated with an organ - Digital Twin associated with the eye*

Creating a Digital Twin associated with the eye can lead to understanding the eye's behavior both structurally and functionally through the interaction of its components. The level of complexity for constructing the eye-associated DT is high, considering not only the main components of the eye (cornea, iris, lens, retina, optic nerve) but also optical properties, focusing system, motor function, light sensitivity, vascularization, and fluid drainage. Modeling the eye highlights simulating the refractive effect of light through the cornea and lens, implicitly adjusting the focus to obtain a clear image on the retina. Light sensitivity can be represented by modeling the photoreceptor cells at the level of the retina (cone cells, rod cells), bipolar cells, amacrine cells, ganglion cells, and adjusting the size of the pupil helps the iris regulate the amount of light entering the eye. Simulating the interactions between the aforementioned types of cells leads to forming an overall image to identify how light signals are processed and transmitted to the brain. Thus, adaptability to light can be achieved through the implementation of motor and sensitivity functions. With the help of the motor function and modeling the parameters of the extrinsic eye muscles, different types of eye movements can be simulated: saccadic, conjugate, tracking.

From the perspective of vascularization, the eye is a highly vascularized organ, and any changes that may occur in the arteries, veins, or capillaries can predispose to the development of pathologies. Additionally, proper drainage of intraocular fluid helps maintain normal intraocular pressure, thus reducing the likelihood of glaucoma. Failure to identify dysfunctions in the drainage system promotes fluid accumulation in the eyes, leading to altered eye function. Moreover, the pathologies that may arise result in structural and functional changes in the eyes, further contributing to the increased complexity of constructing a Digital Twin associated with the eye.

- *Digital Twin associated with a pathology - Digital Twin associated with glaucoma*

The second approach consists of creating a DT associated with a pathology identified at the eye level: DT associated with glaucoma. Creating a DT associated with glaucoma starts with the behavior of the healthy eye both structurally and functionally.

Glaucoma is a progressive eye condition that leads to irreversible vision loss by affecting the optic nerve fibers. Risk factors for glaucoma include elevated intraocular pressure, history of eye trauma, chronic conditions such as diabetes mellitus, prolonged corticosteroid therapy, nearsightedness, and farsightedness, including the presence of hereditary factors.

Identification of structural changes at the level of the optic nerve or retina can be achieved using optical coherence tomography (OCT). Additionally, information from the patient's medical history regarding ophthalmic conditions will be acquired, as well as information obtained from the ophthalmological examination: intraocular pressure value, corneal thickness (below 500 microns), visual acuity, iridocorneal angle measurement, cup-to-disc ratio (0.6-0.8).

With the help of artificial intelligence algorithms and data from patients, simulations will be conducted to identify how increased intraocular pressure and related changes in fluid flow (insufficient drainage of intraocular fluid and its accumulation) affect eye function. The Digital Twin associated with glaucoma also focuses on simulating optic nerve damage, resulting in progressive vision loss and its impact on the patient. For the initial development of this model, clinical databases will be utilized, with the digital model being continuously improved to achieve relevant results. The construction of a Digital Twin associated with glaucoma highlights the integration of engineering concepts with those of ophthalmology, leading to the development of a precise model. This also assists medical staff in selecting the best treatment solution and improving the quality of life for the patient.

- *The Digital Twin associated with the human body - The Digital Twin as a system of systems*

The third approach consists of building a Digital Twin associated with the patient, seen as a system of systems where each organ is considered a system. The first step will be represented by creating Digital Twins associated with organs: Digital Twin for heart, Digital Twin for lungs, Digital Twin for kidneys, Digital Twin for brain, Digital Twin for the liver, Digital Twin for eye, etc. By interconnecting these system-type Digital Twins, the Digital Twin associated with the patient will be created, leading to simulating the integrative functioning of the human body. The interactions between these Digital Twins can help identify issues affecting the proper functioning of the human organism.

After creating the Digital Twin associated with the kidneys and integrating it with the other Digital Twins, following the simulations, the patient was diagnosed with diabetes mellitus. Based on the predictions made, a predisposition towards diabetic retinopathy, a pathology specific to the eyes, was suggested. Through the interaction between these two pathologies, the Digital Twin associated with the patient can identify possible complications that may arise in the circulatory system: arterial hypertension, myocardial infarction, stroke. Thus, continuous monitoring of the patient's health status can be achieved by monitoring physiological parameters, information that will contribute to identifying possible pathologies and suggesting personalized treatments. Additionally, a holistic approach will be created to assist medical personnel in making the best decision regarding the patient's life, highlighting predispositions to certain pathologies and the body's reactions to the proposed medication treatments.

2.2. Digital Twin - Architecture framework for glaucoma identification

One of the objectives of this paper is to present an architectural framework for glaucoma detection and personalised treatment, structured into 3 layers.

In the construction of the general model, aspects related to the anatomy and physiology of the eye will be considered: the component parts (the cornea, the lens, the retina, the optic nerve), as well as the values of the parameters involved in diagnosing this pathology: the cup/disc ratio, the value of intraocular pressure, the thickness of the cornea, the measurement of the irido-corneal angle. Additionally, to facilitate the process of diagnosing glaucoma, the results of clinical studies regarding the existence of risk factors such as age, race, and medical history will be integrated. Based on these basic notions that facilitate the construction of the Digital Twin, various test scenarios will be designed according to the type of glaucoma: primary open-angle glaucoma, closed-angle glaucoma, congenital glaucoma. Thus, in the general model, classical treatment methods will be integrated according to the type of each category of glaucoma, such as monotherapy with antiglaucoma medications, laser therapy, and surgical interventions. The objective of administering treatment in glaucoma is to achieve and maintain the desired intraocular pressure, with a value below 21 mmHg. Another element that must be integrated into the construction of the general Digital Twin is the integration with other pathologies. The presence of eye pathologies such as myopia, uveitis, pseudo exfoliation syndrome, retinal vein occlusion, and ocular traumas can influence the way glaucoma is identified and treated.

The presence of severe myopia leads to changes in the anatomy of the eye, which is a risk factor for the occurrence and progression of open-angle glaucoma. In the case of uveitis, increased intraocular pressure is favored by the blockage of aqueous humor drainage, which can lead to the development of a secondary form of glaucoma. In the case of pseudo exfoliation syndrome, a condition that involves the accumulation of fibrillar material in the eyes, the blockage of the drainage system is favored, which in turn influences the increase in intraocular pressure and the occurrence of pseudo exfoliation glaucoma. Retinal vein occlusion, especially central retinal vein occlusion, is one of the complications that can lead to the development of neovascular glaucoma. Additionally, ocular injuries affect the aqueous humor drainage system, leading to the presence of traumatic glaucoma.

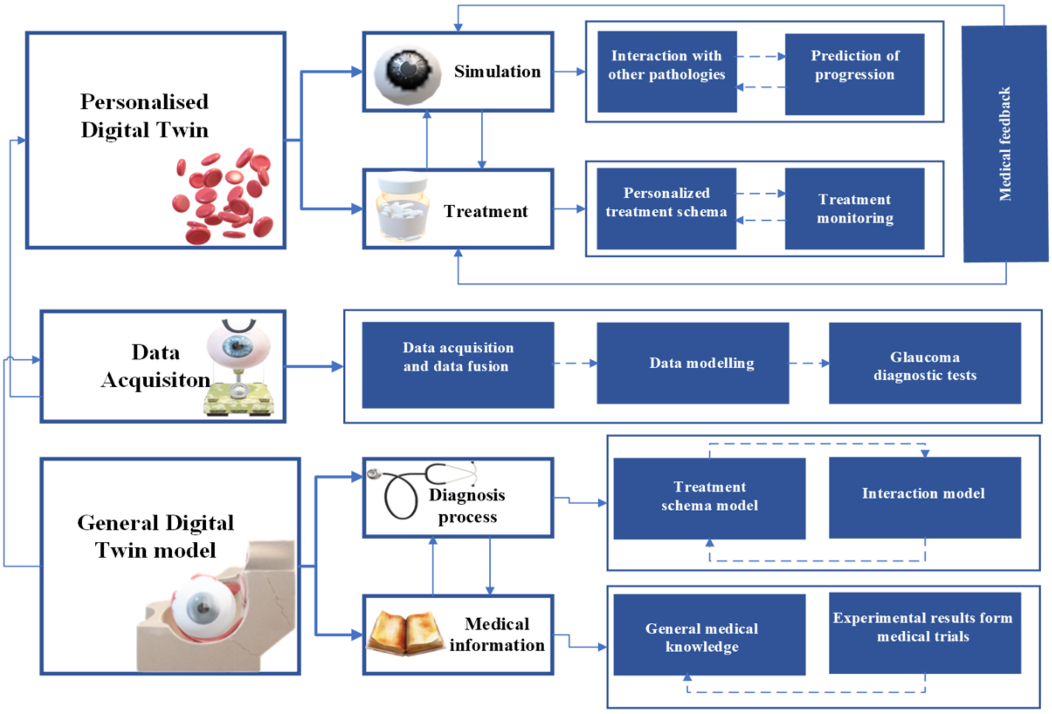

Fig. 1. - Architecture framework for glaucoma identification

However, not only the presence of eye pathologies can influence the progression and treatment of glaucoma. Among the adjacent pathologies, diabetes mellitus and arterial hypertension can be discussed. In people diagnosed with diabetes mellitus, neovascular glaucoma has been noted as a co-pathology. Thus, the presence of abnormal blood vessels on the iris and at the level of the iridocorneal angle has been identified, leading to an increase in intraocular pressure. Regarding arterial hypertension, it affects the blood flow to the optic nerve and in some cases contributes to its deterioration, which favors the occurrence of glaucoma. Taking all these aspects into account, the general model of the Digital Twin for glaucoma diagnosis has been created.

At the next layer in the architecture of the Digital Twin, the focus is on acquiring data that comes from the patient because of the ophthalmological consultation. The second layer involves collecting patient data by performing corneal pachymetry, from which parameters such as intraocular pressure (IOP), irido-corneal angle measurement, and corneal thickness will be obtained. Additionally, regions of interest (ROI) of color fundus photographs (CFPs) of the eye will be used. To ensure continuous improvement of the model and its performance, information from available medical databases, as well as from the patient's medical history, will be integrated. Thus, an overview of the patient's pathologies will be formed, taking into account the identification and integration of correlations regarding the progression of glaucoma, and subsequently choosing an optimal treatment solution. The next step will involve data preprocessing, normalization, and standardization to ensure compatibility among the datasets that will be used. At this layer, with the help of artificial intelligence and prediction algorithms, a glaucoma diagnostic test will be performed. The processes of data acquisition, fusion, and modeling are presented in [8].

Once glaucoma has been identified, a Personalized Digital Twin will be created, which is the third layer of the architecture and contains two additional modules. The first module is intended for personalized treatment, while the second focuses on simulation. There will be bidirectional communication between the two modules to allow for the continuous improvement of the Digital Twin based on the results obtained and feedback provided by the specialist doctor. Treatment scenarios will be developed based on the data obtained from the medical consultation, integrating the medical history, and taking into account the interaction with other pathologies. Thus, the specialist doctor can use the Digital Twin to simulate the effects of administering a new medication on the parameters that influence glaucoma. In this context, the possible adverse reactions of the patient can be determined. If the Digital Twin suggests laser therapy or surgical intervention, the DT can contribute to the planning of the procedure as well as to the optimization of post-operative results by minimizing risks.

Regarding the administration of treatment for a patient diagnosed with two pathologies such as glaucoma and diabetes mellitus, regular monitoring of blood glucose levels is prioritized when administering beta-blockers, which are intended to reduce intraocular pressure. While the administration of these medications leads to achieving the desired IOP, the patient may experience symptoms of hypoglycemia such as palpitations and trembling. On the other hand, the administration of prostaglandins does not affect glucose metabolism but produces local side effects in the eyes such as conjunctival hyperemia, changes in iris color, macular edema, dry eyes, and epithelial erosions.

Regarding arterial hypertension, the concomitant use of topical and systemic beta-blockers can lead to a decrease in heart rate and blood pressure, thereby amplifying systemic effects. Additionally, the administration of carbonic anhydrase inhibitors helps reduce intraocular pressure by decreasing the production of aqueous humor but can cause electrolyte imbalances that affect not only blood pressure control but also the effectiveness of antihypertensive medications. Thus, continuous monitoring of the patient is necessary to adjust the treatment according to the progression of the pathology and its interaction with other conditions. Additionally, collaboration between doctors with different specializations is encouraged to ensure the continuous improvement of the results provided by the Digital Twin. Administering a treatment without considering all the pathologies with which the patient has been diagnosed affects not only the efficacy of the treatment but also the occurrence of side effects.

In conclusion, the acquisition, processing, and integration of data into the general model contributes to the formation of a Personalized Digital Twin, which plays a role in suggesting personalized treatments for glaucoma and predicting the progression of this pathology. By regularly monitoring the patient and continuously improving the algorithms and the prediction model, not only is the quality of life for patients and their relationships with medical staff improved, but the Digital Twin also becomes a diagnostic tool for ocular pathologies that provides personalized treatment suggestions.

3. Materials and Methods

A dataset containing information from 144 patients diagnosed with Open-Angle Glaucoma (OAG), aged between 18 and 80 years old published by the Eye Center at the Second Affiliated Hospital of Zhejiang University (ZJU) - GRAPE dataset [9] was used for the diagnosis of Open-Angle Glaucoma (OAG). The dataset contains associated images of 1556×1556 pixels and 2136×2136 pixels acquired through the TRC-NW8 Fundus Camera and CR-2 PLUS AF Digital Retinal Camera. For each patient, OCT scans of each eye were used: OD - OCT for the right eye, OS - OCT for the left eye. Additionally, regarding gender distribution, 64 women and 80 men were involved. For the construction of this model, the following specific parameters of glaucoma were used: VF (visual field assessment), IOP (initial intraocular pressure) ranging from 8-55 mmHg, CCT (Central Corneal Thickness) measurements (424-610 micrometers), irido-corneal angle measurements. Regarding the values obtained from OCT associated RNFL (retinal nerve fiber layer thickness) measurements, 4 values were obtained: S (for superior), N (for nasal), I (for inferior), T (for temporal), and Mean (average of values between measurements for S, N, I, T). A predictive model for Digital Twins that can be used to predict the onset of glaucoma, has been proposed in the following section and validated with the help of the dataset. The model will be extended to aid in the simulation of the progression of this ocular pathology. Thus, the goal of the model is to predict the evolution of the visual field (VF) and intraocular pressure (IOP) values of a patient after a specific interval of time (years), based on the patient's baseline measurement containing the age, gender, initial IOP, central corneal thickness (CCT), glaucoma category, the initial VF values, and a color fundus photograph (CFP). For the model development, 631 regions of interest (ROI) of color fundus photographs (CFPs) of the eye were used, cropped from the original images. The processing method of the CFPSs for cropping the ROI was highlighted in [3], a task carried out with the assistance of ophthalmologists to identify the cup-to-disc (C/D) ratio, another relevant parameter for the prevention, identification, and treatment of glaucoma. [10] [11] [12]

4. Experimental results

Regarding the model construction, because the dataset contains both images and numeric feature values (mixed data), we used a multiple-input CNN (Convolutional Neural Network), allowing us to handle each data type appropriately. The architecture of the CNN is presented in Fig. 2.

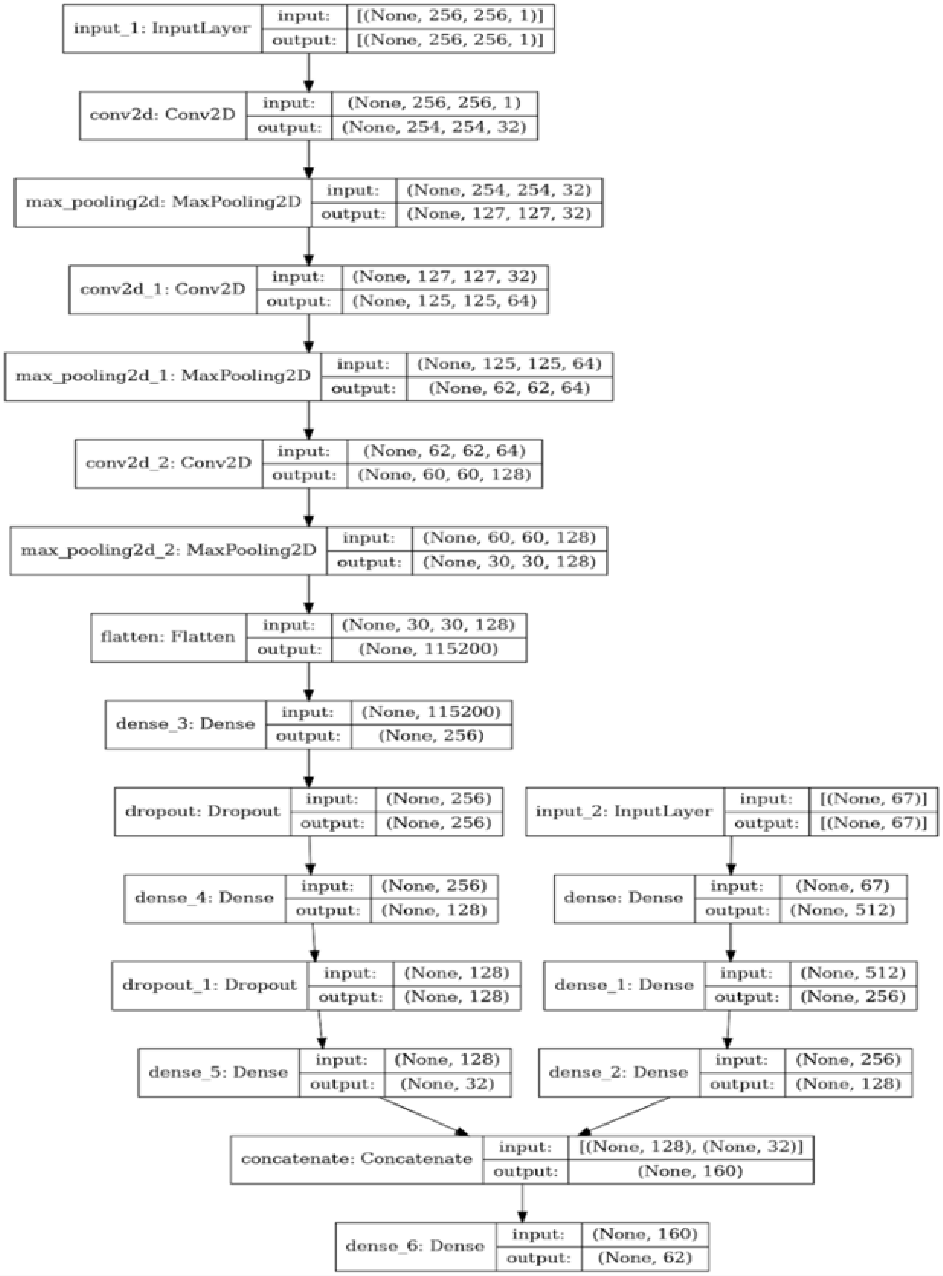

Fig. 2. The architecture of the CNN

The first branch of the network (left) is dedicated to processing the ROI images, while the second (right) branch of the network is dedicated to processing the other features from the dataset. In order to achieve the goal, we had to process the initial dataset. We used a common approach for longitudinal datasets and combined the information from the baseline dataset with the information from the follow-up dataset. For each follow-up measurement we took the time interval after the initial check-up and concatenated it to the baseline values, considering it as a feature. The interval was discarded from the follow-up values and the rest of the values were used as a label.

After this process we obtained a dataset with 1115 elements, with:

- 67 features: time interval, age, gender, IOP, CCT, glaucoma category and 61 VF values,
- 62 labels: IOP and 61 VF values.

For each element in the baseline dataset, we took the cropped region of interest (ROI) images of the CFP and converted them to grayscale and resized them to 256 x 256. After this we proceeded with the normalization/standardization process. For the gender and glaucoma category we used the label encoding technique. For the time interval, age, IOP, CCT and VF features we used a Min-Max scaler. We stored the min and max values for each type of feature in order to be able to convert the prediction of the model to readable data. The values were normalized to the [0, 1] interval. The VF values might contain -1 values and as mentioned by the authors of the GRAPE dataset, they represent blind spots. We chose to keep these values as -1 and only normalize the positive values, thus having VF values between [-1, 1]. After the normalization process, the data was split into train (90%) and test (10%) subsets

We trained the network with 15 epochs using a batch size of 16. The loss function used was the mean squared error (MSE). The Adam optimizer was used with a learning rate of 0.001.

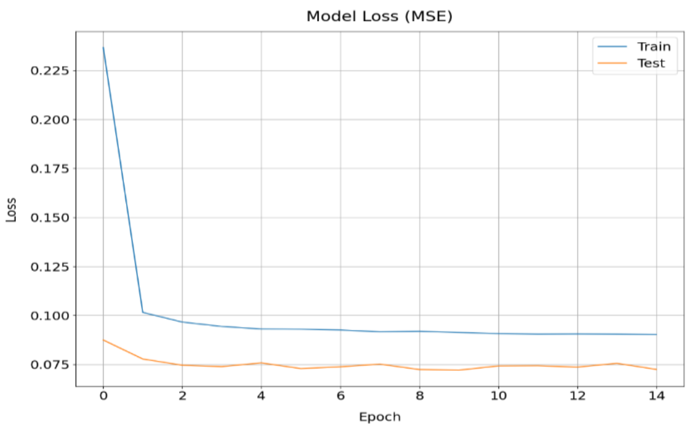

Fig. 3. The loss functions – MSE

We also used the mean absolute error (MAE) metric in order to interpret the results more easily. As we can see, MSE and MAE converge in a similar fashion.

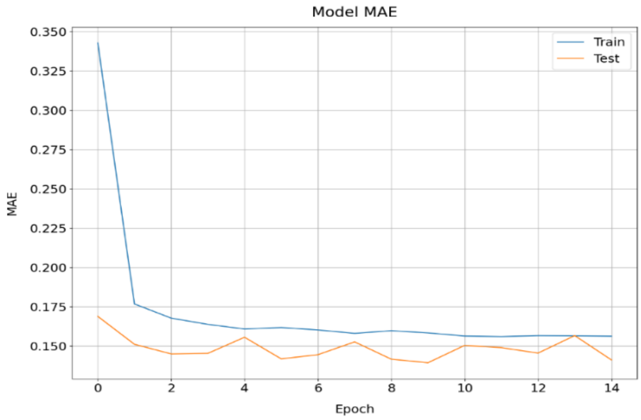

Fig. 4. The mean absolute error - MAE

In [13], the results were obtained by training a CNN for 50 epochs, while in the present work, 15 epochs were used with a batch size of 16. In [13], the MAE error obtained was 4.143 for CFPs, 4.029 for ROI of CFPs, and 4.107 for ROI with OD/OC segmentation. As for the root mean square error (RMSE), Huang et al. obtained the following values: 5.627 for CFPs, 5.474 for ROI of CFPs, and 5.596 for ROI with OD/OC segmentation. In this work, MSE and MAE converge in a similar fashion.

To evaluate the effectiveness of the prediction model for visual field (VF) progression and intraocular pressure in glaucoma, the sensitivity and specificity of the network must be analyzed, which will be presented in future research. The results obtained using MSE and MAE indicate consistency between the two metrics, implying a stable and reliable performance of the model.

5. The use of Digital Twins in ophthalmology clinics: benefits and limitations in glaucoma diagnosis

The development of a Digital Twin for identifying glaucoma can be associated with numerous challenges and limitations that need to be addressed to ensure diagnostic accuracy.

One of the limitations may be the complexity and precision of the model [14]. Since glaucoma is influenced by multiple factors such as intraocular pressure, corneal thickness, cup-to-disc ratio, and associated fundus images, accurately modeling the interactions between these parameters requires the implementation of complex algorithms and the existence of properly processed data. [15]

Another challenge may be the integration of heterogeneous data from different sources, which have different formats and structures, and their use requires advanced preprocessing and normalization techniques. The presence of errors in the data affects the results provided by the Digital Twin, potentially leading to an incorrect diagnosis for the user. Thus, the performance of the model will be affected. Additionally, the presence of co-pathologies such as hypertension must be considered, as they impact not only the identification of glaucoma but also the treatment suggestions provided by the Digital Twin. In this context, collaboration among medical specialists from various clinical fields is recommended to provide continuous feedback that helps improve the accuracy of the results provided by the Digital Twin. [16]

The adaptation and personalization of the Digital Twin must be carried out continuously through data collection from the patient [17]. It is noteworthy that updating the values involved in glaucoma diagnosis can only be done during ophthalmologic consultations, as there are no sensors to acquire these values from the patient in real-time. In this context, data updates will only be carried out by medical staff, emphasizing the development of continuous learning algorithms to support the improvement of the model.

Another limitation may be the confidentiality and security of patient data used in the diagnostic process [18]. This raises concerns not only about patient consent but also about the strict adherence to data protection regulations. Implementing security measures to prevent unauthorized access and misuse of data must be a priority to ensure the safety of patients' confidential information. [19]

Additionally, the validation and clinical acceptance of the Digital Twin, which is used only as a decision support tool for medical staff, are also brought into discussion. Rigorous testing of the models and validation through clinical studies contribute to diagnostic accuracy, providing a significant potential for glaucoma management. [20]

In summary, addressing the aforementioned limitations supports technological development and collaboration among specialists from various fields, facilitating the development of effective solutions for glaucoma diagnosis. The development of advanced retinal image processing techniques and the continuous training of prediction algorithms, along with collaboration with medical specialists, increases the accuracy of the results provided by the Digital Twin. Failure to comply with data confidentiality and security leads to ethical risks, necessitating the implementation of an architectural framework with layers dedicated to patient data confidentiality and security.

5.1. Discussion – The use of Digital Twins in ophthalmology clinics

The development of a Digital Twin for identifying glaucoma can be associated with numerous challenges and limitations that need to be addressed to ensure diagnostic accuracy.

One of our objectives is the application of the Digital Twin at the level of ophthalmology clinics and offices.

The first stage involves acquiring the necessary infrastructure for collecting and processing patient data. This includes the use of hardware and software capable of managing large volumes of data and supporting image processing. [8]

The second stage emphasizes the collection of data involved in glaucoma diagnosis from patients. Collecting and storing data in a standardized format facilitates the integration of data that will be used in the glaucoma identification process. Analyzing patient data and monitoring the evolution of the pathology involves using data from previous consultations, which contributes to suggesting a personalized treatment based on the patient's needs.

The development and implementation of the Digital Twin associated with the pathology represents the next stage following the acquisition of corneal pachymetry data and integration with the medical history. Thus, a personalized Digital Twin will be constructed to provide optimal treatment suggestions. The Digital Twin will be tested on historical data sets to validate diagnostic accuracy and ensure the efficiency of the results.

Additionally, organizing training sessions for medical staff on interpreting the results provided by the Digital Twin is also discussed, along with providing procedures for adhering to data security and confidentiality protocols to avoid any ethical issues. Thus, among the advantages of using the Digital Twin are continuous monitoring of glaucoma progression and personalized treatment based on each patient's individual profile. Creating specific treatment plans for each patient, along with continuous monitoring of the pathology's progression, allows for rapid interventions and adjustments to prescribed medications based on the model's predictions. Additionally, by processing and analyzing large volumes of data, diagnostic accuracy can be improved, and the costs associated with preventing complications and optimizing the resources used in patient treatment can be significantly reduced.

The use of Digital Twins in ophthalmology clinics may be associated with high initial costs for acquiring the necessary hardware and software infrastructure, as well as employee training. Additionally, managing and maintaining a Digital Twin requires ongoing costs for updates and technical support, and the use of large volumes of data raises concerns about data security and confidentiality. Regarding the acceptance of Digital Twin usage by medical staff, there may be reluctant to adopt this technology because its integration brings changes to existing workflows.

Among the future research directions, the interaction with other pathologies that can affect not only the identification of glaucoma but also the treatment suggestions is discussed. One of the co-pathologies that will be involved in future research is hypertension. Additionally, clinical studies are planned to validate the efficacy and clinical benefits of using the Digital Twin in ophthalmology.

Prediction algorithms will be improved, thus increasing the accuracy and reliability of predictions. There is also an aim to integrate the Digital Twin with other emerging medical technologies, such as remote monitoring devices.

The application of the Digital Twin in ophthalmology clinics and offices brings significant benefits in glaucoma management, but also a series of challenges that need to be addressed, supporting interdisciplinary collaboration and continuous research.

6. Conclusions

This paper presents various approaches to building a Digital Twin in the field of medicine, especially in ophthalmology. The aspects motivating the high level of complexity in creating a Digital Twin associated with the eye are discussed. In this case, the simulation process must take into account not only the main components of the eye but also optical properties, focusing system, motor function, light sensitivity, vascularization, and fluid drainage. Thus, the emphasis is on using a convolutional neural network that utilizes a multi-modal dataset of longitudinal follow-up visual field and fundus images for glaucoma management.

An initial model has been developed for predicting glaucoma and the progression of this pathology based on various parameters such as age, gender, IOP, central corneal thickness, glaucoma category, the initial VF values, and a color fundus photograph.

In conclusion, the Digital Twin serves as a decision support tool for medical professionals. The model will be continuously updated based on feedback received from the specialist doctor to ensure diagnostic accuracy and to suggest the best option for personalized treatment.

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