DEPARTMENT OF INFORMATICS

TECHNISCHE UNIVERSITÄT MÜNCHEN

Master's Thesis in Informatics

A Web-based Breathing Exercise System for Assisting the Treatment of Chronic Obstructive Pulmonary Disease (COPD)

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Ein Webbasiertes Atemübungssystem zur Unterstützung der Behandlung von Chronisch Obstruktiver Lungenerkrankung (COPD)

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I confirm that this master's thesis in informatics is my own work and I have documented all sources and material used.

Munich, 16.08.2021 Elçin Can Çavuşoğlu

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Abstract

Chronic Obstructive Pulmonary Disease (COPD) is a major respiratory disease that causes difficulty in breathing and reduces health-related quality of life. Throughout their respiratory physiotherapy (pulmonary rehabilitation) treatment, COPD patients need to perform breathing exercises at home by themselves. Without the supervision of healthcare professionals, patients have difficulties in performing their exercises alone, and healthcare professionals have no control over patients' health status outside the clinical setup. This thesis aims to develop a system that assists COPD patients with their self-breathing exercises and provides their physiotherapists a data-driven overview of patients' health status and exercise performance at home. To achieve this, a case study including a survey and interviews are conducted with physiotherapists. After understanding the current challenges of the treatment and requirements of the system, the practical approach that consists of detecting the proper breathing pattern, and a web-based assistive system is developed. To evaluate the accuracy of the developed algorithm that detects the proper breathing pattern as well as the usability and efficiency of this approach in the treatment of COPD, this system is integrated into the treatment process of physiotherapists and their COPD patients for two weeks. The results indicate the acceptable accuracy of the algorithm and usability of the system. They also show the interest of both physiotherapists and patients in using this system on their further treatment processes.

Contents

1. Introduction

This chapter explains the motivation for this work, defined objectives, research questions as well as the structure of this master's thesis.

1.1. Motivation

Everyone cares about their breathing and respiratory health. However, the lung is a vital, and at the same time a vulnerable organ. It can be easily affected by injury or airborne infection and cause to a chronic respiratory disease such as Chronic Obstructive Pulmonary Disease (COPD) [1]. COPD can limit lung functionality and health-related quality of life by causing hardship in performing the most basic activities such as walking, getting in and out of bed, or getting into and out of a chair [2].

Respiratory physiotherapy (pulmonary rehabilitation) is a highly effective treatment for COPD patients. Nevertheless, COPD patients struggle with this treatment because between the sessions with physiotherapists, patients need to continue their treatment by themselves at home. Patients have difficulties in performing their breathing exercises correctly without the supervision of physiotherapists. Moreover, they have difficulties in pursuing such a regular exercise regimen due to a lack of discipline and motivation even though they know that this treatment is vital for them. On the other side, respiratory physiotherapists have no supervision over their patients' exercise performance, well-being, or health status at home. In other words, they don't know whether their patients are performing their breathing exercises at home, how their health status is, or whether they are struggling at some specific parts of their self exercises.

To address these challenges of respiratory physiotherapy treatment, the main idea of this thesis is to develop a web-based system that assists both physiotherapists and their patients in the treatment of COPD.

Previous research on providing solutions to the treatment of COPD has mostly focused on assistive hardware devices. COPD patients use non-digital tubular solutions such as "spirometry" or "triflow" for their breathing exercises. These devices support patients in gas trapping and airflow, improving their capability of gas volume exchange [3]. There are other researches that focus on wearables or multi-sensor devices to get physiological signs of COPD patients [4], as well as mobile sensors for the usage of sound signals of COPD patients during their breathing exercises [5].

Different from the previous research focus on the treatment of COPD, this thesis offers a web-based solution to assist the breathing exercises of COPD patients, while monitoring them and providing them feedback in real-time based on their performance.

This solution also aims to serve physiotherapists by enhancing their treatment without physical presence, enabling them to keep track of their patients' home exercise performance and to have better control over their treatment with a data-driven overview. The evaluation of this solution is planned to be conducted in a clinical setup with 4 physiotherapists and 5 COPD patients from Germany and Turkey, by integrating this solution into their treatment for a period of two weeks.

1.2. Objectives and Research Questions

The main objective of this thesis is to develop an accurate and highly usable assistive breathing exercise system that increases the efficiency and satisfaction of the COPD treatment both for physiotherapists and their patients. To begin with, the first part of this research focuses on understanding an effective breathing exercise and the relevant metrics for determining the proper breathing pattern. Therefore, the first research question is:

RQ1: *What are the relevant and measurable metrics of an effective breathing exercise for the treatment of COPD?*

After the research on an effective breathing exercise and the measurable metrics for the proper breathing pattern, the focus of the research becomes to develop an algorithm that evaluates a breathing exercise according to the measurable metrics that are learned from the previous research question:

RQ2: *How can an algorithm be developed from the relevant metrics to accurately evaluate the breathing exercise?*

Once the technical implementation of the algorithm and a system integrated with this algorithm is done, the next goal of the research are is to evaluate the implemented system's efficiency for the treatment of COPD:

RQ3: *From the perspective of physiotherapists, how does this approach improve the efficiency of the COPD treatment?*

Finally, the last research question aims to evaluate the usability of this system in the treatment of COPD by both physiotherapists and their patients:

RQ4: *How usable is this approach in the treatment of COPD from the perspectives of patients and physiotherapists?*

1.3. Thesis Structure

The content of the rest of this thesis for each chapter is described as follows:

Chapter 2 describes the relevant subjects as a background knowledge that are valuable for the reader to understand the described concepts better in the following chapters.

Chapter 3 describes the previous researches and works that focus on the treatment of COPD.

Chapter 4 describes the breathing exercises for COPD patients, as well as a conducted case study that is used to provide answers to the RQ1.

Chapter 5 describes the functional and non-functional requirements of the system that are collected based on the challenges of COPD treatment both for physiotherapists and their patients.

Chapter 6 explains the architecture of the system that is designed based on the requirements of the system that are collected in Chapter 5.

Chapter 7 provides answers to the RQ2 by providing a detailed description of the implementation of the algorithm that detects the metrics for the proper breathing pattern, as well the web-based system.

Chapter 8 presents the evaluation approach and the evaluation results, thus provides answers to the RQ3 and RQ4.

Chapter 9 discusses the analysis of the results that are presented in Chapter 8, and describes the limitations of the implemented system.

Chapter 10 concludes the thesis by summarizing the research and describes the suggestions for the future work.

2. Background Knowledge

This chapter describes Chronic Obstructive Pulmonary Disease (COPD) and respiratory physiotherapy (pulmonary rehabilitation) treatment, which are valuable to understand the described concepts in the following chapters better.

2.1. Chronic Obstructive Pulmonary Disease (COPD)

Chronic Obstructive Pulmonary Disease (COPD) is one of the major chronic respiratory diseases that affects around 200 million people globally. COPD causes 3 million people to die yearly, which makes it the third most deathly disease in the world [1]. It blocks the airways of patients with inflammation, causing progressive dyspnea (shortness of breath), phlegm, and cough [2, 6]. These symptoms affect the patient's daily life by causing muscle weakness, which consequences in reduced exercise performance and physical inactivity in daily life. The causes of the disease are tobacco smoking, as well as air pollution and occupational dust [2]. A cure for COPD does not exist. However, respiratory physiotherapy (pulmonary rehabilitation) treatment is very effective for COPD patients to strengthen their lungs and muscles, and regain their health-related quality of life.

2.2. Respiratory Physiotherapy (Pulmonary Rehabilitation)

Respiratory physiotherapy is a therapeutic treatment process for patients that are suffering from chronic respiratory diseases, especially from COPD [7]. The core components of this treatment consist of exercise training with healthcare professionals, as well as self-management of patients.

The exercise training component of the treatment can be divided into two segments of exercises: physical body exercises and breathing exercises. The physical body exercises serve to increase muscle strength of patients that was weakened because of restricted physical activity caused by shortness of breath and fatigue [7]. On the other hand, the breathing exercises serve to strengthen the respiratory muscles of patients, which prevents the blockage of the patients' airways and enhances tissue oxygenation [8]. Hence, this reduces the shortness of breath on patients. Both physical body training and breathing training increases the patients' health-related quality of life.

The self-management of patients is an essential part of the respiratory physiotherapy treatment process. In this treatment process, patients usually go to rehabilitation clinics or practices and perform one-on-one exercises with physiotherapists. Between these one-on-one sessions, patients need to continue their treatment by performing physical body and breathing exercises by themselves. In the scope of this thesis, the research focuses on patients' self-breathing exercises that they perform at home without the supervision of physiotherapists.

3. Related Work

This chapter describes some of the previous researches and works that focus on the treatment of COPD. Considering the objectives and the scope of this thesis, the related works and researches can be examined in two groups. The first group consists of studies and researches on the breathing techniques and exercises of COPD patients. The second group maintains the researches and works on providing digital solutions to COPD treatment.

3.1. Breathing Techniques for COPD Patients

Rik Gosselink (2004)

In his research, Rik Gosselink discusses the efficacy of the breathing techniques and several breathing exercises such as pursed lip breathing, diaphragmatic breathing, forward leaning position, inspiratory muscle training, and active expiration [9]. His research studies the efficacy of these breathing exercises for reducing COPD patients' symptoms such as dyspnea (shortness of breath), and physiological effects, while increasing patients' respiratory muscle strength, optimizing thoracoabdominal motion, and improving gas exchange with reducing dynamic hyperinflation [9]. The results of his studies indicate the evidence of effectiveness for the pursed lip breathing exercise in improving oxygen saturation, dyspnea, and recovery of breathing pattern, which are especially beneficial for patients with emphysema. In addition, the results also showed the effectiveness of inspiratory muscle training for strengthening the inspiratory muscles, improving dyspnea and health-related quality of life [9].

Liliane Mendes et. al (2019)

Liliane Mendes et. al have studied the effects of diaphragmatic breathing exercise and pursed lip breathing exercise on the shortness of breath, and chest wall kinematics and asynchrony of COPD patients [10]. The research assessed the effects of diaphragmatic breathing exercise that is performed alone, and in combination with the pursed lip breathing exercise. The results indicated that both approaches increased the chest volume, and improved breathing pattern by reducing the breathing frequency. However, no specific effects are observed on both exercises against dyspnea [10].

3.2. Digital Solutions for the COPD Treatment

Most of the previous research on providing digital solutions to COPD treatment has focused on assistive hardware devices or sensors.

Desen Cao et. al (2018)

In their research, Desen Cao et. al provide an assistive system for the respiratory physiotherapy treatment of COPD patients, which uses a wearable multi-sensor system for obtaining the physiological signs of the patients [4]. The system in their research is studied in different areas of the treatment such as 24 hours inpatient monitoring, breathing exercise training with breathing pattern analysis, and six minute walk tests, including a total number of 130 patients [4]. According to the results of their studies, their wearable multi-sensor system accurately provides information on the vital signs of patients during their treatment [4].

Wenyao Xu et. al (2013)

Different from the research that focuses on a system for obtaining the vital signs of COPD patients on the different parts of the treatment, Wenyao Xu et. al present a mobile phone based system that focuses on the lung function diagnosis and the breathing exercises of COPD patients in their treatment [5]. Considering its focus on the patients' self-breathing exercises, their work is highly related to our research. Their approach uses mobile phone's microphone-based sensors to detect sound and vibration signals that are created by the air pressure of patients' breathing [5]. Their practical approach uses sensing, signal processing, modeling, and calculation. It also maintains gamification for the exercises of patients to motivate them on performing their daily exercises. Their system is evaluated with 40 subjects, and is considered to be used for the remote treatment of COPD according to their experimental results [5].

In this thesis, our approach focuses on the effective breathing exercises for COPD patients, which are described in Section 3.1. Our practical approach differentiates from the assistive hardware device or sensor approaches that are described in Section 3.2, by focusing on breathing pattern detection with a software-based solution that assists the treatment of COPD.

4. Case Study

This chapter provides answers to the *RQ1: What are the relevant and measurable metrics of an effective breathing exercise for the treatment of COPD?* In other words, it explains the relevant and measurable metrics of an effective breathing exercise for the treatment of COPD. It also describes the breathing exercises that the system aims to provide for patients. It includes a case study that is conducted based on semi-structured and structured interviews with physiotherapists to understand the challenges of them as well as their patients through the current treatment process.

4.1. Breathing Exercises

Stress volume of COPD patients directly effect their disease, thus their breathing [8]. Patients get stressed when they have difficulties in breathing and with increasing stress, breathing becomes even more challenging, and this loop continues. By reason of this, patients need to learn how to control their breathing by exercising controlled breathing techniques. Learning these techniques will enable patients to manage their own breathing, decrease their exertion while breathing, and enhance the condition of their respiratory muscles. These techniques enhance tissue oxygenation, while decreasing blood pressure and heart rate of patients [8].

There are three exercises to practice controlled breathing: pursed lip breathing, diaphragmatic (belly) breathing, and positioning. Pursed lip breathing is a very significant exercise type for patients' recovery, especially when they suffer from dyspnea (shortness of breath) [8]. Diaphragmatic breathing exercise helps patients strengthen their muscles of respiration. Different from these two exercises, positioning exercise assists patients when they feel tiredness or weakness [8]. In the scope of this thesis, the focus of the research is on the pursed lip breathing and diaphragmatic breathing exercises.

4.1.1. Pursed Lip Breathing Exercise

Pursed lip breathing exercise is essential when patients struggle shortness of breath. This exercise slows down the breathing of the patient, allowing more oxygen from the air to enter patients' lungs during inhalation, as well as more carbon dioxide (waste gas) to be exhaled.

This exercise is performed with two instructions:

- Breathe in (inhale) through your nose.
- Breathe out (exhale) through your mouth with pursed lips as blowing out a candle.

These instructions are based on a one to two ratio between the inhalation and exhalation instructions. For instance, when the patient inhales for two seconds, then the exhalation should be four seconds. The durations for inhale and exhale are dependent on the patient's status and ability to breathe. Focus on this exercise should be more on the exhaling part.

The airways in the respiratory system branch into smaller airways from the throat towards the lungs, such as the root branches of a tree, ending up in the small air sacs called alveoli. These alveoli perform the gas exchange following the change of pressure and concentration. When patients are performing pursed lip breathing exercise and exhale slowly with pursed lips, this action creates back pressure in the patient's lungs. This pressure keeps the airways open, thus enabling more waste gas to go out. Since more carbon dioxide goes out, there is more room in alveoli for oxygen coming in with the next inhalation. This is the main goal of this exercise [8].

4.1.2. Diaphragmatic (Belly) Breathing Exercise

Diaphragmatic (belly) breathing exercise is crucial for strengthening the respiratory muscles. Since this exercise focuses on using the respiratory muscles, it enhances the proper breathing skills of patients as well as strengthening their diaphragms [8].

This exercise is performed with two instructions:

- Breathe in (inhale) deeply through your nose.
- Breathe out (exhale) through your nose.

Patients need to focus on their inhalation on this exercise. When they take a deep breath, the air should go all the way down to the bottom of their lungs and expand their diaphragm. To ease the understanding of the patients, they are usually instructed to put one hand on their stomach and the other hand on their chest. Hence, they can feel the expansion of their diaphragm while trying to keep their chest more steady during breathing in [8].

Diaphragm's movement enables the airflow in and out of the airways from the alveoli in the lungs. In case of weak diaphragm movement, if the airways collapse and prevent the waste gas to go out, oxygen cannot move into the lungs. This causes shortness of breath. The diaphragm of patients that are suffering from COPD becomes flattened with time. Because of this, patients mostly use their intercostals (accessory muscles) to breathe instead of using their diaphragm since their diaphragm is less functional. Therefore, diaphragmatic breathing exercise is very effective against shortness of breath by learning how to use diaphragm while breathing, and strengthening it [8].

4.2. Interview Process

In order to understand the metrics of the proper breathing pattern as well as the current treatment process and its challenges for both the physiotherapists and their patients, I conducted detailed semi-structured interviews with a physiotherapist and structured interviews with 20 physiotherapists.

4.2.1. Metrics of the Proper Breathing Pattern (RQ1)

Although there are different types of breathing exercises for COPD patients including different instructions and their duration, the main metrics for detecting the proper breathing pattern are equivalent for all the breathing exercises. The reason for this is all the different types of breathing exercises are based on inhale and exhale commands. For instance, even though the exhale command of an instruction can differ between "exhale from your nose for four seconds" and "exhale from your mouth for six seconds as blowing out a candle", the proper breathing pattern is determined with the same metrics.

While the patients are doing these exercises at a practice, the physiotherapists assist them by providing instructions, displaying them where the patients should focus on their bodies as well as correcting them. In order to understand the metrics for measuring whether the patient is performing the exercise correctly with the naked eye, I conducted an interview with a respiratory physiotherapist in Munich. According to this detailed interview about the proper breathing pattern on the breathing exercises, I found out that there are three main metrics that physiotherapists check to determine whether the patients are performing the exercise correctly or not.

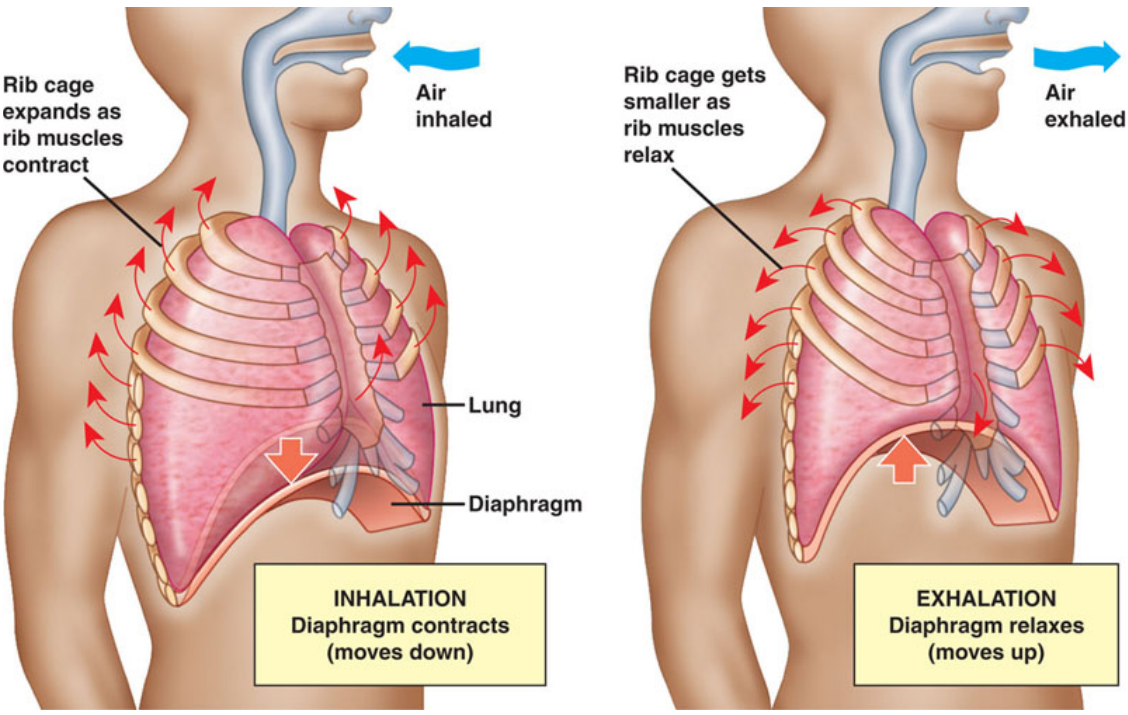

Figure 4.1.: Expansion and contraction movements of the diaphragm and the ribs[1]

The first and the most important metric for determining the proper breathing pattern is the **expansion** and **contraction movements on the patient's belly** while conducting the inhale and exhale commands respectively. This is based on breathing through the diaphragm. In addition to the expansion and contraction movements on the patient's belly, the physiotherapist also mentioned another evidence of the body that is visible to the naked eye and easy to feel by touching the patient's belly for determining these movements. When the patient inhales and expands the belly, the lower ribs covering the diaphragm contract towards inside. On the other hand, when the patient exhales and the belly contracts, the same ribs go out and are easy to see or feel. These movements are shown in Figure 4.1. The physiotherapist stated that they tell their patients to put their hands on their lower ribs covering the diaphragm in order to feel the movement on their belly and their ribs, and therefore feel and control their own breathing.

Furthermore, another important metric for the proper breathing pattern is the patient's **shoulder movement**. For the correct breathing, the patient needs to use the respiratory muscles including the muscles of inspiration and expiration. The inhalation is the active part of breathing and the correct shoulder movement in the inhalation should be based on these accessory muscles of inspiration such as sternocleidomastoid and scalene muscles. Sternocleidomastoid, which helps us rotate the head, elevates the sternum during inhalation. Moreover, scalene muscles that are responsible for the flexion of the neck, elevate the upper ribs. In consequence of these elevations on both the sternum and the upper ribs, little rise on the upper body during the inhalation is natural. However, COPD patients have weakness in their respiratory muscles, thus they have problems doing the breathing exercise by using the above explained muscles alone. Instead, they use their neck muscles that support them, especially during inhalation.

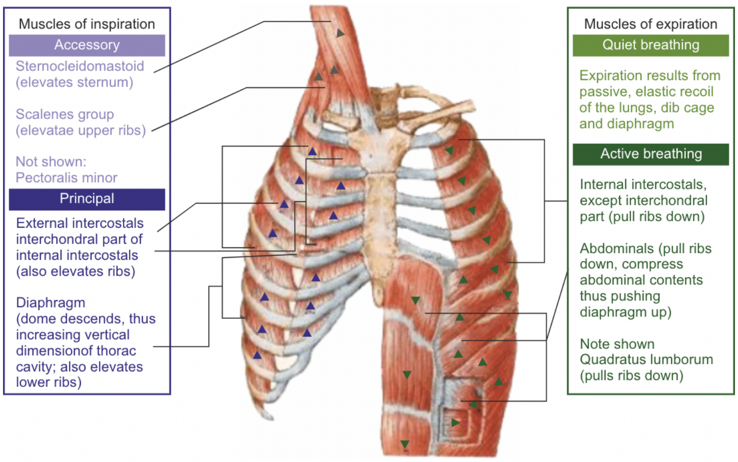

Figure 4.2.: Respiratory muscles[2]

[1] https://step1.medbullets.com/respiratory/117007/muscles-of-respiration

[2] https://www.chegg.com/learn/biology/anatomy-physiology-in-biology/expiration-and-inspiratory-muscle

The physiotherapist explained this issue as getting little help from the neck muscles can be tolerated. However, the patients need to learn not to use them. In fact, this is a very significant movement that needs to be detected during the breathing exercise because the wrong application of the inhalation might lead to not improving the breathing of the patient since they do not exercise the correct muscles. Therefore, the second metric for the proper breathing pattern is defined to detect whether the shoulders of the patient increase more than a tolerable amount during the inhalation. This tolerable amount is considered as approximately 1 cm.

Another important metric for the proper breathing pattern is the patient's **body posture** during the exercise. According to the physiotherapist, patients need to have their upper body in an upright position, and their back straight. "This is one of the biggest challenges of the patients. Correct sitting is very important and most of the time the patients fail because of sitting wrong.", the physiotherapist stated. For the best outcome of the exercise, she mentioned that sitting while doing the exercise is the optimal position. Because when patients stand and try doing the exercise, they have weak control of their bodies for standing in an upright position. On the other hand, when patients sit during the exercise, they focus better on their bodies. Hence, detecting the patient's body posture while doing the exercise is another essential metric for the proper breathing pattern.

4.2.2. Survey design

In addition to the interviews with a physiotherapist to understand the relevant and measurable metrics of an effective breathing exercise, which are described in the previous subsection, I also designed an exploratory survey[3] for the physiotherapists. The survey was designed for physiotherapists, who have specialization in respiratory physiotherapy and are currently working either at a practice, rehabilitation clinic or hospital. The survey included 22 questions and was divided into 4 sections: (1) questions about their expertise and institution, (2) questions about their challenges for providing treatment, (3) questions about the patients' challenges, and (4) questions about using a digital system for assisting the treatment that they provide to their patients. The aim of this survey was to understand the current treatment process, challenges of physiotherapists or institutions that prevent them to provide better care for their patients, and challenges of patients during their treatment.

This survey focused more on understanding how the previously explained research topics work in practice. In other words, it combined the literature understanding of COPD, respiratory physiotherapy, and breathing exercises with the actual treatment process in practice, and its challenges for both the physiotherapists and the patients.

[3]See appendix.

4.2.3. Survey results

The survey was conducted to 20 physiotherapists, who are currently working as a physiotherapist at a practice, rehabilitation clinic or hospital in 4 different states in Germany, namely Bavaria, Baden-Württemberg, North Rhine-Westphalia, and Rhineland-Palatinate, as well as in Steiermark state in Austria. The physiotherapists, who are between 21 and 62 years old, have an average age of 35.5 years old. 13 out of 20 physiotherapists are currently working at a practice, six at a rehabilitation clinic, and one at a hospital. The overview of the information about the participants can be seen in Table 4.1.

Table 4.1.: Physiotherapists that participated in the survey.

State	**No. of Physiotherapists**	**Institution**	**Average Age**
Bavaria	13	Practice, Rehabilitation Clinic	34.4
Baden-Württemberg	2	Practice	28
North Rhine-Westphalia	2	Practice, Hospital	43
Rhineland-Palatinate	2	Practice, Rehabilitation Clinic	45
Steiermark (Austria)	1	Practice	31

According to the survey results, a physiotherapist treats on average 13 patients each day, spending approximately 27 minutes per patient. Their preparation and follow-up time after each patient takes more than five minutes. Survey results showed that the continuity of physiotherapy treatment is very significant and essential for chronic respiratory diseases with a weighted score of 8.74 out of 10 according to the evaluation of the physiotherapists.

The results indicate that there are three main categories that cause the insufficiency of the respiratory physiotherapy treatment for both the physiotherapists and the patients: access to professional physiotherapy, statutory health insurance system, and lack of awareness and motivation of the patients.

Firstly, the physiotherapists stated that one of the biggest challenges that prevent them from providing better care for their patients, as well as more patients, is the capacity limitation. There is a lack of physiotherapists specialized in respiratory physiotherapy and 30% of the respiratory physiotherapists can not accept new patients due to low capacity.

Moreover, physiotherapists mentioned that the statutory health insurance system affects the continuity of the treatment of patients suffering from chronic diseases negatively. According to them, since the health insurance companies would like to budget their expenses, either they do not prefer to cover all the costs of the treatment thus pay only for a specific part that requires the patients to complement the treatment price. Or, they do not want to cover the treatment costs continuously for a longer period. Hence, patients suffering from chronic respiratory diseases are restricted from accessing continuous prescriptions for their treatment. On the other hand, this also directly affects the treatment duration. As a consequence of this strategy of the statutory health insurance system, the physiotherapists believe that the duration of the therapy sessions is shorter than it should be. Hence, they lack time during the treatment to supervise the patient for a longer period and make the treatment more efficient.

Furthermore, the lack of awareness and motivation of the patients is also a very significant reason that reduces the efficiency of the treatment. In addition to statutory health insurance system, physiotherapists also expressed that some physicians restrict the treatment by lacking of recognition about the effectiveness of physiotherapeutic applications. Since these physicians do not provide a prescription for respiratory physiotherapy treatment, patients are unaware of this treatment. In the case that patients are prescribed to physiotherapy, they need to continue their treatment besides the one-on-one sessions with the physiotherapist, by doing self exercises at home. Even though they know that this treatment is vital for them, they have difficulties in pursuing such a regular exercise regimen due to a lack of motivation and discipline. On the other hand, physiotherapists have no control over the patients' exercise performance, health status, and well-being outside of the practice. According to the survey, 100% of the physiotherapists stated that they give their patients homework for doing self exercises at home. Nevertheless, they do not know whether patients are doing their exercises, how well they are performing, or if they are struggling at some specific things. This is one of the major factors affecting the motivation of patients since they don't have a physiotherapist at home, who is supervising their exercise. Physiotherapists mentioned that lacking control over the patients outside the clinic also prevents them from making the treatment more efficient.

Besides the challenges of the current respiratory physiotherapy treatment, survey results also showed that using an assistive digital solution is believed to improve the efficiency of the treatment. 90% of the physiotherapists stated that they would use digital solutions to improve the continuity of the therapy. 70% of the therapists expressed that they would benefit from digital solutions to lengthen the duration of the treatment. 65% of them mentioned that they would use digital solutions that allow them to provide better care for their patients at home and allow them to have more control over the patient activity outside the clinic. However, 95% said that they do not use any digital solutions for their treatment even under lockdown during the COVID-19 pandemic.

5. Requirements for Breathing Exercise Monitoring and Analysis System

This chapter describes the functional and non-functional requirements for developing a monitoring and analysis system for assisting the breathing exercises of COPD patients. These requirements are defined considering the relevant and measurable metrics for the proper breathing pattern as well as the current treatment process and its challenges for both the physiotherapists and their patients. We conducted several interviews with a physiotherapist, who is specialized in respiratory physiotherapy treatment for both patients suffering from cystic fibrosis and COPD. Working iteratively with the physiotherapist, the functional and non-functional requirements for the breathing exercise monitoring and analysis system, which would benefit both physiotherapists and patients, are defined.

5.1. Functional Requirements

5.1.1. Real-Time Detection of Proper Breathing Pattern

The first problem that the system tackles is the patient's motivation for doing self-breathing exercises at home without the physical existence and supervision of a physiotherapist. The existence of an assistive system at home, similar to a physiotherapist, is believed to increase patient's motivation. In order to do this, the system should be developed to assist patient's breathing exercises by monitoring patient activity and analyzing in real-time whether the patient is performing the exercise correctly. This requires the detection of proper breathing pattern. Therefore, the system needs to detect the three main metrics for the proper breathing pattern, namely the belly expansion, shoulder movement, and body posture, as described in section 3.2.1.

5.1.2. Live Feedback on Patient Performance

Apart from these detections, it is also very significant that the system provides feedback in real-time to the user depending on their performance, letting them know what they are doing correctly or wrong. Since this helps the system to virtualize the physiotherapist experience, it is believed to motivate patients on doing their exercises at home.

5.1.3. Patient Exercise Program View

Another requirement on the system for motivating patients on doing their home exercises is to keep them up to date with their treatment and progress. To achieve this, the system requires a display for showing patients their exercise program, and same day's exercise overview to start if they have a pending assigned exercise on that day.

5.1.4. Exercise Customization

On the other side, tackling physiotherapists' challenge of lacking control on patient's treatment process outside the clinic, the system shall provide a data-driven monitoring and evaluation of patient's exercise performance at home. In order to allow the physiotherapist to keep control of the treatment, it is decided to enable the physiotherapist to control the exercises of their patients. In other words, the system needs to allow the physiotherapist to customize an exercise and assign it to her patients individually. The physiotherapist mentioned the importance of this individual customization of the exercises by stating that patients have different capabilities for inhaling and exhaling. While some patients can inhale for three seconds and exhale for six seconds, these durations can cause problems to others who are capable of doing them only with a shorter duration.

5.1.5. Patient Health Status Scale Evaluation

Additionally, the system should share patients' exercise performance and well-being at home with their physiotherapists for enabling them to keep track of their patients' health status outside the clinic. The physiotherapist explained that they use Borg Rating of Perceived Exertion (RPE) scale evaluation for determining the patient's well-being before starting the therapy session at the clinic. RPE is a scale evaluation for assessing a person's exertion and effort, fatigue, and shortness of breath through physical activity, and is often used in occupational health. It has a numerical score list between 6-20 that determines the level of exertion, where 6 corresponds to "no exertion at all" and 20 to "maximal exertion". [11] The physiotherapist told that they simply ask questions to the patient and depending on the answers, they rate the patient on the scale. So as to have the system aligned with the actual one-on-one therapy sessions of the respiratory physiotherapy treatment at the clinic, the physiotherapist stated the necessity for having the RPE scale evaluation on the system.

5.1.6. Patient Exercise Performance Details View

On top of providing physiotherapists the health status of their patients through the RPE scale evaluation, the system shall also include detailed and individual exercise performance of patients to be displayed to their physiotherapists. This is a crucial requirement on the system since it aims to increase the efficiency of the treatment for the physiotherapists by enabling them to keep track of their patients' exercise performance outside the clinic and providing continuous treatment opportunity. According to the physiotherapist, this exercise performance data should be displayed with different options to therapists. Firstly, she was interested in seeing whether a patient did his exercises or not throughout the week. Secondly, she was interested in seeing the details of a specific exercise of a patient. Therefore, the system needs to have an overview of whether a patient did his exercises and another view of the patient's exercise performance in detail.

5.1.7. Exercise Instructions and Explanatory Videos

Other than the main requirements of the system, some minor requirements are also defined. To ease the usage and understanding of how to use the system for patients, the system shall include explanatory videos. These videos should show the patients how to use the system for doing the breathing exercises as well as specific explanations of each breathing exercise. The system shall also provide instructions for the exercises in written and audio formats. Providing audio instructions is a significant necessity of the system. Since the patients need to perform the exercise sitting sideways towards the computer, it is hard and at the same time not healthy for patients to turn their heads towards the screen and read the instructions while continuing the exercise.

5.1.8. Warnings and Precautions

Last but not least, the system should provide a warning for patients before starting the exercise, letting them know to stop the exercise immediately in case they feel dizzy or have any abnormal symptoms. It also needs to prevent patients to do their assigned exercises more than once.

5.2. Non-functional Requirements

5.2.1. Compatibility

The system is planned as a web-based application, thus physiotherapists can use it on any electronic device that has an internet connection and includes a web browser. Since the application aims to monitor patients' exercise performance, it requires a camera device for receiving video stream in real-time. Therefore, to use the system, patients need to have a computer that has an internet connection and a web camera connected to it.

5.2.2. Environment and Conditions for Proper Breathing Pattern Detection

Real-time analysis of patients' exercise performance considering the proper breathing pattern arise some limitation requirements for the patients. These requirements can be divided into two segments: obligatory and preferable (but not necessary) requirements.

First, for the computer vision algorithm to correctly detect the belly expansion of patients from a 2D image sequence, patients are obligated to position themselves sideways in front of their camera while performing the exercise. Additionally, the camera has to see their body uninterruptedly from their head down to their hip. These are the only two obligations of the system. However, for the computer vision algorithm to extract and contour the patient's body in an optimal way, the system also has preferable (but not necessary) requirements. For instance, it requires patients to place themselves having a white or a slightly light-colored wall in the background, that is different from their clothing color. Moreover, the body and belly movements should be clearly seen for better analysis. Consequently, they need to wear a tight t-shirt, or optimally, to be shirtless such that their body and belly movements can be clearly seen with the naked eye.

5.2.3. Availability

In addition to the requirements for patients, the computer vision algorithm's image processing time is also very critical for the availability and usability of the system. Since the system aims to display the exercise performance of patients including providing feedback, the computer vision algorithm should respond within 0.5 seconds in order to prevent the video stream to freeze and cause a bad user experience. Besides the bad user experience, the delay in the computer vision algorithm's response would lead to the wrong detection of the proper breathing pattern. Hence, it is very critical that the response time is short and aligned with the instructions of the exercise and their duration.

5.2.4. Medical Software Regulations

Since the system is developed to be used in the medical industry and to have a medical purpose, it needs to fulfill regulatory requirements. The most important regulatory requirement for the development of this system is the GDPR (General Data Protection Regulation). GDPR is a legal requirement for protecting a person's data with the principles of confidentiality, integrity, accuracy, transparency, purpose limitation, data minimization, and storage limitation. According to GDPR, health data can only be processed if the person has specifically consented or the data is necessary for medical treatment, as well as if the data is of public interest or the system assures high-quality protection and standards [12]. Therefore, in order to fulfill this critical regulatory requirement, the system should be developed in a *privacy by design* structure.

6. System Architecture

This chapter describes the overview and architecture of the implemented system. Firstly, it explains the tasks that the system aims to address. It also describes the infrastructure as well as approaches, tools, and technologies that were used to develop a breathing exercise monitoring and analysis system considering the requirements that were discussed in the previous chapter.

6.1. System Overview

The scope of this thesis is to develop a web-based system that would assist the treatment of COPD both for respiratory physiotherapists and their patients. Regarding the requirements that were discussed in Chapter 5, the goal of this system can be divided into two components: providing a digital assistant for the breathing exercises of patients, and a digital treatment software for physiotherapists and their patients.

6.1.1. Digital Breathing Exercise Assistant

To begin with, this system aims to provide a digital assistant for the breathing exercises of patients by instructing them on how to perform a proper breathing exercise, while monitoring them and providing them feedback in real-time based on their performance. This component digitizes the breathing exercises of patients that are normally conducted at the clinic in a one-on-one setup with physiotherapists. Instead of doing their breathing exercises with physiotherapists, patients can perform their breathing exercises at home through this system without the physical presence of physiotherapists, but still receiving feedback from the system based on their performance. In other words, the system virtualizes the physiotherapist experience for patients. To achieve this, the system addresses the detection of the proper breathing pattern in real-time. This detection is done over the video stream that is captured from patients' web-cam, which is integrated into their computer.

6.1.2. Digital Treatment Software

This system also intends to provide a digital treatment software for both physiotherapists and their patients. Through this digital treatment software, physiotherapists can customize breathing exercises individually for their patients and assign to them. They can keep track of their patients' home exercise performance in detail, as well as well-being at home based on a data-driven overview.

Moreover, this digital treatment software also serves to enable patients to continue their treatment process at home. It keeps them on track with their treatment by showing them their daily and weekly exercise program, and their progress.

6.1.3. System Architecture Overview

The system's architecture can be considered in two different components: the backend of the system that contains the computer vision algorithm and management of exercise system data, and the frontend of the system for the user interface that is used for exercise configuration and execution, and performance display. Figure 6.1 shows a high-level overview of the system architecture.

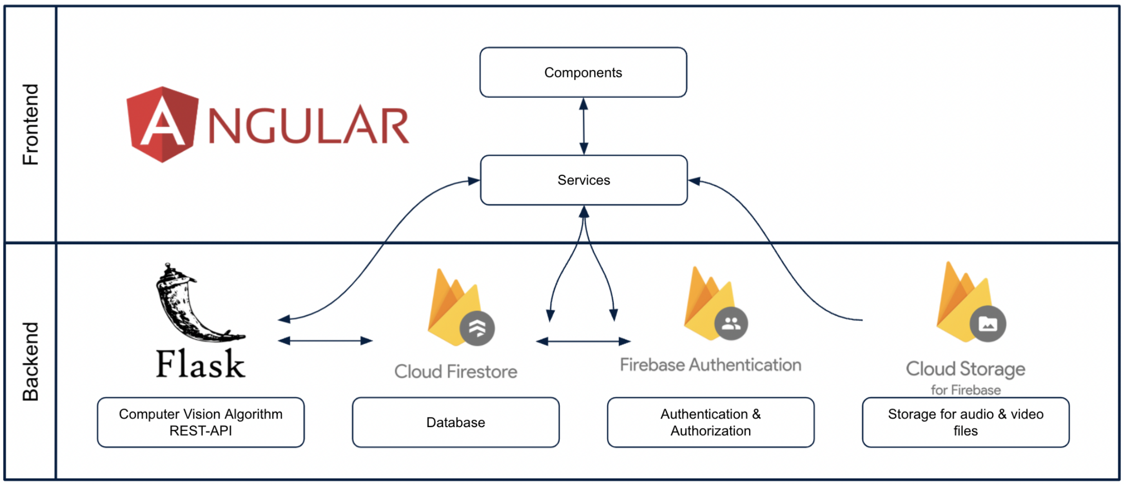

Figure 6.1.: High level overview of the system architecture

On the backend side of the system, a computer vision algorithm handles the image processing and determining the proper breathing pattern. The backend also contains a database for storing and retrieving user data as well as data that is extracted during image processing, and endpoints for the connection and transfer of these data to the frontend. Flask[1], which is a web framework of Python, is used for the backend development of the system. The backend architecture is designed over Google Cloud Platform[2] and its products. The system uses Firebase's[3] Cloud Firestore as its database for storing user and exercise data. It also uses Firebase's Cloud Storage for storing the explanatory videos and audio files containing exercise instructions. Last but not least, the system uses Firebase Authentication for the authentication and authorization of users. The backend server is deployed on a Compute Engine virtual machine in the Google Cloud Platform.

[1] https://flask.palletsprojects.com/en/2.0.x/
[2] https://cloud.google.com/
[3] https://firebase.google.com/

On the other side, Angular[4], which is a TypeScript[5] based framework for web application development, is used for frontend development. It communicates with the Flask backend of the application through Flask's REST-API and HTTP calls for retrieving data from the database and serves the user interface for the users. It also uses its services with HTTP calls to directly communicate with the Cloud Firestore database and Cloud Storage for retrieving static data, as well as Firebase Authentication. This communication is handled through Firebase's easy-to-use and secure Software Development Kit (SDK) as well as AngularFire library which is the official Angular library for Firebase. The frontend server is deployed and hosted in Firebase Hosting.

6.2. Frontend Architecture

The frontend architecture of the system uses the Angular framework for the development of the web-based application. This web-based application is developed based on the framework's fundamental architectural concepts. A root module gathers multiple components and services of the system, which are separated logically according to the system's functionality, logic, and data. According to Angular's architectural concept, components define different views of the application, and services provide functionalities to these views in order to make the program reusable and efficient[4].

In our system, there are five views, namely *Login View*, *Physiotherapist View*, *Patient View*, *Patient Details View* and *Exercise View*. The frontend architecture of the system, contains five different components for these views: *Login Component*, *Physiotherapist Component*, *Patient Component*, *Patient Details Component* and *Exercise Component*. The frontend architecture also maintains TypeScript concepts. By relying on these concepts, data flow on the frontend architecture is designed and separated considering different type interfaces, which are aligned with the stored data on the database. As a complement, services that provide functionality and data to the components are also divided considering the same type of interfaces.

6.2.1. Frontend Architecture for Digital Breathing Exercise Assistant

In the frontend architecture, *Exercise Component* addresses the requirements for the digital breathing exercise assistant. This component provides patients a view where they can perform their breathing exercises in front of their computer, see themselves in a gamified view, and receive feedback in real-time while performing the exercise.

Exercise Component enables computer's web camera upon user allowance and displays live view of users in a web camera mirror view. Once they start the exercise, live mirror view of patients changes to live gamified view of patients to assist them in better understanding their body movement. During the exercise, this component provides audio and text instructions on how to perform the exercises as well as a countdown

[4] https://angular.io/
[5] https://www.typescriptlang.org/

timer for the duration of each instruction. Text instructions and the countdown timer are displayed at the bottom of the view. It also provides feedback in real-time based on the performance of patients on the three detection types, namely belly expansion, body posture, and shoulder increase. This real-time feedback is displayed on the right side of the view.

On top of this live mirror view, this component also maintains a video frame, where explanatory videos are displayed for patients before they start the exercise. The first video type explains patients how to use their computer and the system for performing the breathing exercises with the digital assistant. It includes the personal setup in front of the screen as well as positioning the camera angle, to address the environment and condition requirements for the proper detection of the breathing exercise as described in Section 5.2.2. This is very significant for addressing the requirements of the digital breathing exercise assistant, especially for the camera to capture patients' bodies uninterruptedly from their head down to their hip. The second video type explains patients how to perform that specific exercise, which they will start performing after the explanatory videos. When patients start the exercise, the component removes the explanatory video frame out of the view.

6.2.2. Frontend Architecture for Digital Treatment Software

Since the system serves physiotherapists and patients for different purposes, the user interface of the system is divided into two different parts: a user interface for physiotherapists, and another for patients. *Login Component* serves to address this division. It contains a view with a login page where users are directed to their individual interface based on their role. In other words, once the users log in through this page, *Login Component* directs physiotherapists to the physiotherapist user interface, and patients to the patient user interface.

User Interface for Patients

Patient Component is responsible for the patient user interface of the digital treatment software. It maintains a single view that contains personalized information on individual patient's treatment. This view provides a calendar where patients can see their weekly exercise program. In other words, the component displays patients on a weekly calendar view, on which days their physiotherapists assigned them exercises, as well as the type of these exercises. These exercises on the calendar are colored in red, yellow, and green labels for patients to keep track of their own progress. A red label means the patient did not do an assigned exercise on the previous dates. The green label stands for the performed assigned exercises. The yellow label stands for the upcoming assigned exercises in the future dates. Under the calendar view, *Patient Component* also shows patients their remaining exercises for that specific day, including details such as exercise type, duration in sets, and deadline of the exercise.

User Interface for Physiotherapists

The user interface for physiotherapists is designed with two components, namely *Physiotherapist Component* and *Patient Details Component*. Just like the user interface for patients, the user interface for physiotherapists is also personalized for the individual user. *Physiotherapist Component* provides a view where physiotherapists can see a list of their patients that they treat through this system, with an overview of information about them. Below this view, *Physiotherapist Component* also provides a view with a list of exercises, which are on the system and can be assigned to the patients. By choosing a specific patient on the patient list view, this component directs the user to the *Patient Details Component*.

Patient Details Component provides detailed information on the treatment of the selected patient. Similar to the weekly calendar view on the *Patient Component*, *Patient Details Component* provides a view with a weekly calendar on top of the screen, where physiotherapists can see the assigned exercise program of the patient. They can also see whether the patient did the assigned exercises or not, on the previous dates of the week. Different from the weekly calendar of the *Patient Component*, *Patient Details Component* also serves for displaying the selected exercise performance details of the patient to the physiotherapists. By clicking on a specific exercise on the calendar view, this component pops up a window with the questionnaire answers of patients before and after the exercise as well as these questionnaires' RPE scale evaluation. Below the questionnaire answers, it displays the exercise performance details including the correct score of instructions both for inhale and exhale overall. It also displays on which detection the patient failed to perform correctly.

6.3. Backend Architecture

The backend architecture of the system consists of four components as described in Section 6.1.3: *Flask Web Server*, *Cloud Firestore Database*, *Firebase Authentication*, and *Firebase Cloud Storage*.

Flask Web Server plays a crucial role in this architecture by maintaining the Computer Vision algorithm and the REST-API. Python is one of the most used programming languages for computer vision development and supports numerous libraries and resources for it. Hence, using Python and one of its frameworks for the Computer Vision algorithm was essential for the backend architecture of the system. In addition to the advantages of Python, it is also significant to point out that the Flask framework is specifically chosen for the development of the web server since it is a micro web framework of Python. A micro-framework includes either minimal or no dependencies, thus makes the developer independent from third-party libraries or pre-defined structures. It makes the development of backend code easier without the need of protocols or low level-code[6]. It is based on Werkzeug[7] (a Web Server Gateway Interface library) and Jinja2[8] (a design-friendly templating language for Python).

Furthermore, the rest of the backend architecture is designed over Google Cloud Platform. Google Cloud Platform (GCP) is a platform that offers developers and companies several technology services and products to build their products in a secure, scalable, and efficient way. The backend architecture of the system uses Firebase and its products. Firebase is a GCP product that enables developers and companies to develop scalable mobile and web applications without managing the infrastructure.[9] The system uses Firebase's *Cloud Firestore Database* as its database, for storing all the user and exercise-related data. It keeps the data in collections and documents, and lets developers structure the data how they want. It also enables access to it without the need for a server through its web SDK. In addition to the *Cloud Firestore Database*, the system uses *Firebase Authentication* service for the authentication and authorization of the users through the entire system. Both *Cloud Firestore Database* and *Firebase Authentication* are integrated to each other and enable strong user-based security. Finally, the system also uses Firebase's *Cloud Storage* for storing the audio files for exercise instructions and the explanatory video files. Similar to the other Firebase products, *Cloud Storage* can also be integrated with *Cloud Firestore Database* and *Firebase Authentication* for the overall integration and user-based security.

6.3.1. Backend Architecture for Digital Breathing Exercise Assistant

Flask Web Server is the main responsible component that addresses the requirements for the digital breathing exercise assistant. The Computer Vision algorithm, which is developed within the *Flask Web Server* is the basis of this system since the system aims to monitor and analyze patient's breathing exercises. In concept, the Computer Vision algorithm targets to detect the proper breathing pattern by processing the retrieved images that are captured by the video stream of the web camera, which is integrated into patients' computers. It processes images using computer vision techniques and extracts data from these images. Besides maintaining the Computer Vision algorithm, *Flask Web Server* also serves to enable the communication and image transfer between the frontend and the backend through its REST-API. This REST-API also enables storing the extracted data in the *Cloud Firestore Database*.

On the other hand, *Cloud Storage* component addresses the requirements for the digital breathing exercise assistant by storing and providing access to the audio instructions during the exercise. It also stores and provides access to the explanatory videos, which are displayed to the user before the exercise for explaining the usage of the system as well as the specific exercise instructions.

[6] `https://dev.to/amigosmaker/what-is-flask-used-for-2do5`
[7] `https://wsgi.readthedocs.io/en/latest/what.html`
[8] `https://jinja.palletsprojects.com/en/2.10.x/`
[9] `https://firebase.google.com/`

6.3.2. Backend Architecture for the Digital Treatment Software

Firebase Authentication component is responsible for the authentication of signed-up users to log in to the system. Since it is integrated with the *Cloud Firestore Database*, it serves to identify the users and enable the system to personalize the user interface for the authenticated user. *Cloud Firestore Database* stores all the data related to the system in its collection and document-based database. The collections and documents within the *Cloud Firestore Database* are designed considering the specific use case of the digital treatment software. Based on *Firebase Authentication*'s directives on users and authorizations, *Flask Web Server*'s REST-API serves to query and find data in the *Cloud Firestore Database* and provide it to the frontend for the user interface of the digital treatment software.

7. Implementation

This chapter describes the implementation of the system and provides answers to the *RQ2: How can an algorithm be developed from the relevant metrics to accurately evaluate the breathing exercise?* It elaborates the approaches, chosen tools, and used technologies for the implementation considering the system architecture that is described in the previous chapter. It also explains the implementation process of the Computer Vision algorithm that detects the three proper breathing pattern metrics. Moreover, it tells about the implementation process of the database design, web application, and the designed user interfaces for different views including the screenshots of the system.

7.1. Database Design

As it is mentioned in the previous chapter, the system uses Firebase's *Cloud Firestore Database*, where data is stored in collections and documents. To design the database structure with minimal collections and documents, the architecture of the system and the relevant data schemas for each component of the architecture are analyzed. Considering the system architecture that is described in the previous chapter, the system provides two different user interfaces for patients and physiotherapists. Since these two user interfaces differentiate from each other based on their views, the data that they display, and the features, the system needs two different data schemas for patients and physiotherapists to ease the data flow. On the other hand, since both patients and physiotherapists are users and have similar user properties on a higher level, the system maintains another data schema for users which both patient and physiotherapist data schemas can inherit from. Finally, both patients and physiotherapists deal with exercise-related data. However, their actions and the relevant exercise data differentiate from each other. Hence, the system has an additional data schema for exercises that can be commonly used by both patients and physiotherapists depending on their needs.

This analysis clarified that all the data in the system can be collected under four main collections. Therefore, the database structure uses four different collections to store the entire data of the system. These four collections are *Users Collection*, *Physiotherapists Collection*, *Patients Collection*, and *Exercises Collection*.

Users Collection maintains users as documents. All documents have a *user id* as document ids to enable reference access. They store general user-specific data such as *first name*, *last name*, *email*, and the *user id* of users. As mentioned in Section 6.2.2, the system directs users to the patient or physiotherapist user interface regarding their role after successful login. To enable this, *Users Collection* also maintains an attribute called *role* which keeps the role information of a user whether he is a patient or a physiotherapist. Using this attribute data, the system directs users to their appropriate user interface.

Additionally, the *user id* that is stored in the *Users Collection* comes from the automatically generated user id of the users in the *Firebase Authentication* component. This enables the integration of *Cloud Firestore Database* and *Firebase Authentication* components that eases the data request flow upon authentication of users.

Exercises Collection has exercises as documents. Similar to the *Users Collection*, all exercise documents have an *exercise id* as their document ids. They store exercise-specific data such as the *exercise id*, *name*, *category*, *sets* as amount of repetition sets that the exercise needs to be performed, as well as the specific instructions of exercises. The instructions of the exercises stores every instruction including its duration and text values.

Physiotherapist Collection keeps physiotherapists as documents. Equivalent to the previous collections, it also keeps all its documents having the *user id* of each physiotherapist. They store the *user id*, *first name*, and *last name* of the physiotherapist. They also store a list of patient ids. These ids refer to the patients that they treat through this system. Moreover, they store a list of exercise ids. These are the ids of exercises that are enabled on their profile, which they can assign to their patients.

Patients Collection maintains patients as documents. All its documents have a *user id* of patients, similar to all the previously described collections. Besides storing general patient data such as *user id*, *first name*, *last name*, and *illness* of the patients, these documents also store detailed exercise-related data. This exercise-related data can be divided into two different segments. The first segment consists of data that is used for the assignment of exercises to patients. This includes a list of exercise ids that the patient is assigned to, as well as customized parameters of exercise instructions for each exercise assigned to the patient. The second segment consists of the detailed exercise performance of patients. This includes the exercise program of the patient ordered by dates, answers of the patient to well-being questionnaires before and after the exercises with their scale evaluation score, and exercise performance results of the patient with performance score and specific errors that he made during each exercise.

Users Collection connects to *Physiotherapists Collection* and *Patients Collection* using the *user id* attribute as a reference. *Physiotherapists Collection* uses exercise ids as a reference to *Exercises Collection* and patient user ids as a reference to *Patients Collection*. *Patients Collection* uses exercise ids as a reference to *Exercises Collection*. These relationships between collections are shown on the Entity Relationship Diagram (ERD) in Figure 7.1.

7.2. Computer Vision Algorithm (RQ2)

The previous chapters already mentioned the significance of the Computer Vision algorithm for the system. Since it is the basis of the system for detecting the proper breathing pattern of patients in real-time, the implementation of the system started with

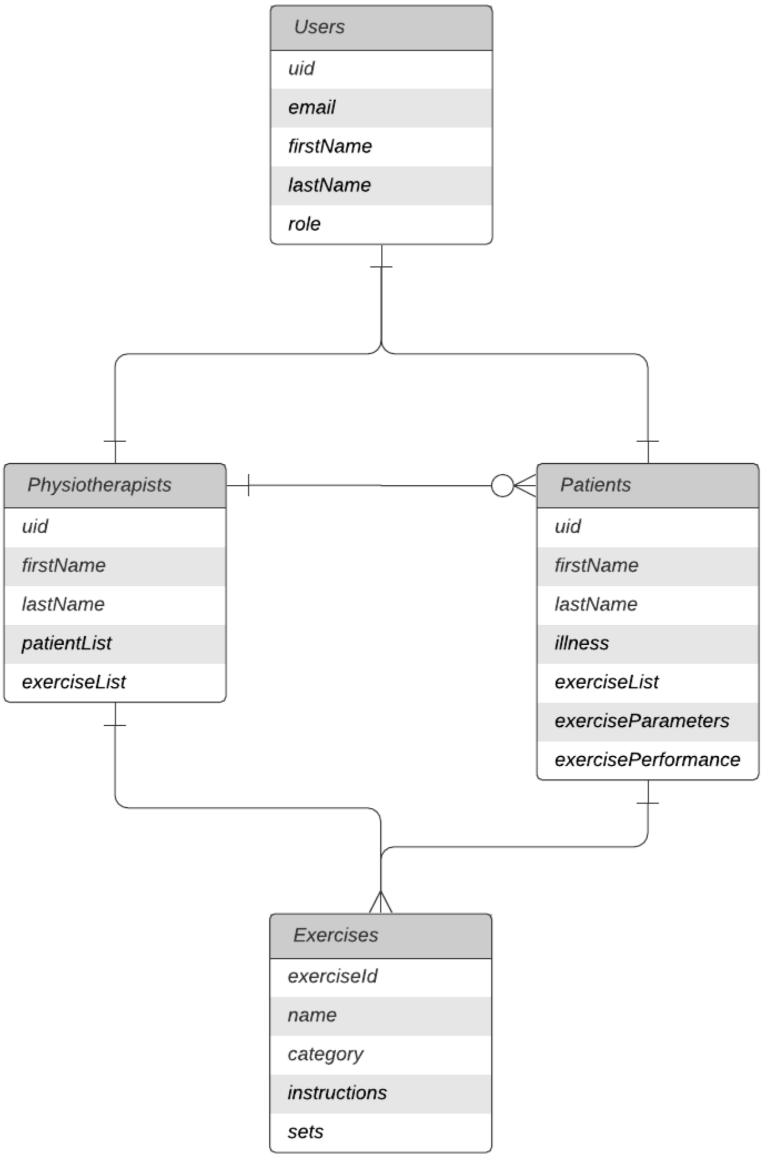

Figure 7.1.: Entity Relationship Diagram (ERD) of the database

the development of this algorithm.

To detect the proper breathing pattern, the algorithm shall first separate the patient's body from each image that is received from the camera of the patient's computer. After separating the human body from the rest of the image, it shall observe the patient's body movement on defined specific parts in terms of the three main metrics for the proper breathing pattern, which are described in Section 4.2.1.

7.2.1. Approach Analysis

To begin with, research on finding the most suitable approach and tools to implement this component is conducted. Based on the research, two main approaches were found for the development of such an algorithm.

OpenCV Contour Detection Approach

The first approach is the contour detection of objects with OpenCV, which is a Computer Vision library for real-time detection. This approach is used for detecting the borders of an object and localize the borders on a given image.[1] Example usage of this approach on a dog can be seen in Figure 7.2. For our system, this approach could be used for detecting the contour of the human body on the images that are received from the computer's camera.

Figure 7.2.: An example usage of OpenCV approach on a dog[1]

Body Parts Segmentation Model Approach

Secondly, it is found out that there are already trained machine learning models for body parts segmentation[2,3]. In other words, these models take an image as input, separate the human body from the rest of the image, and divide it into different body parts such as head, upper body, shoulders, arms, and legs. These models could be used for separating

[1] `https://learnopencv.com/contour-detection-using-opencv-python-c/`

[2] `https://github.com/tensorflow/tfjs-models/tree/master/body-pix`

[3] `https://github.com/PeikeLi/Self-Correction-Human-Parsing`

the patient's body from the rest of the image in our system. Different from the OpenCV approach, these models could also be used for observing a patient's body movement on specific parts since it divides the detected body into body segments. As this approach was more promising in terms of its integrity to the described task for our system, it is decided to use such a machine learning model for the development of the Computer Vision algorithm.

After the decision of using a machine learning model for human body detection, another research is conducted on different models which can be used for our system. As a result of this research, a model that is trained using the Self-Correction for Human Parsing (SCHP) [13] is chosen to be used for the development of our system. This SCHP strategy, a purification strategy, uses an already learned model and boosts the model's performance and accuracy by iteratively aggregating this model with corrected labels [13]. Figure 7.3 illustrates the difference between the output of the ground truth (GT) of a model and the output of the same model after increasing its performance and accuracy with SCHP, given the same input.

Figure 7.3.: Difference between SCHP and GT outputs given the same input image[13]

There are three models which are trained using the SCHP strategy: LIP, ATR, and Pascal-Person-Part. For the development of our system, the Pascal-Person-Part model is used since it focuses directly on body parts segmentation. The model divides the input image into seven parts: background, head, torso, upper and lower arms, and upper and lower legs. The model contains more than 3000 images on its dataset and its validation is 71.46%.[4]

7.2.2. Development

Computer Vision algorithm is implemented within the *Flask Web Server* using Python programming language. The algorithm uses several libraries such as PIL[5] (Python

[4] https://github.com/PeikeLi/Self-Correction-Human-Parsing
[5] https://pillow.readthedocs.io/en/stable/

Imaging Library), PyTorch[6] (an open-source machine learning library), matplotlib[7] (a plotting library), scikit-learn[8] (a machine learning library), NumPy[9] (a scientific computing library), and OpenCV[10].

The algorithm is structured within an endpoint, which receives an image as an input. This input image is a single image frame which is taken from the video stream that is captured from the computer's camera. This image is provided from the frontend of the application that calls the endpoint.

The algorithm then uses the Pascal-Person-Part model with SCHP strategy, which is already loaded and evaluated on the *Flask Web Server*, to separate the patient's body from the rest of the image, and segment the patient's body into body parts. In more detail, the input image received from the endpoint is put into the Pascal-Person-Part model. Pascal-Person-Part model evaluates the input image through its dataset with more than 3000 images and provides an output image which is colored in different color labels separating different parts of the body and having the rest of the image (background of the image) in black color. Then, the algorithm takes this colored image of the human body including different body parts, and uses image processing techniques to detect the three metrics, namely belly expansion, shoulder increase, and body posture of the patient. For the belly expansion detection, the algorithm detects the width of the patient's body, at the height of the diaphragm's position. For the shoulder increase detection, the algorithm calculates the height of the patient's shoulders. For the body posture detection, the algorithm detects the posture of the patient's back. These detections are done through processing each image and extracting the indicators of the patient's body movement on different parts.

The algorithm uses these indicators with the help of linear and polynomial regressions and compares them with the sequence of previously received images to determine the difference of the body movement through time. Since the algorithm needs to detect the continuous behavior of the patient instead of the patient's body structure on a specific timestamp, the comparison of the result with the sequence of previously analyzed images is very significant. In the end, the endpoint containing the Computer Vision algorithm returns only the colored image to the frontend, to be displayed to the patient. However, the algorithm stores the detection results as well as the extracted indicators on an object. Hence, the results of the detection for the proper breathing pattern can then be retrieved through another endpoint, which returns the detection for the three metrics considering the sequence of images that are received throughout each instruction's entire duration. Figures 7.4 and 7.5 show the input and output images received and returned by the Computer Vision algorithm.

[6] `https://pytorch.org/`
[7] `https://matplotlib.org/`
[8] `https://scikit-learn.org/`
[9] `https://numpy.org/`
[10] `https://opencv.org/`

Figure 7.4.: Example of an input image frame of a patient performing the exercise

Figure 7.5.: Example of an output image from the Computer Vision algorithm

7.3. Main Views and Core Features of the Web Application

After the development of the Computer Vision algorithm and the related endpoints that return the results of the proper breathing detection on the *Flask Web Server*, the second phase of the implementation was the development of the web application. In this phase, a web application is developed including different views, core features, and services, which complement the previously developed Computer Vision algorithm by integrating it to a web-based system that patients and physiotherapists can use on their treatment.

Firstly, an Angular project is created including *AppRoutingModule*. This routing module enables the routing between different views on the application. Our system consists of five different views, including *Login View*, *Patient View*, *Physiotherapist View*, *Patient Details View*, and *Exercise View*. Considering the architecture of the system, the routing module of the application consists of three different routes for *Login View*, *Patient View*, and *Physiotherapist View*. Since *Exercise View* is only accessed from *Patient View*, its component *Exercise Component* is called by *Patient Component* for directing users to its view. Likewise, since the *Patient Details Component* is only accessed from *Physiotherapist View*, the *Physiotherapist Component* calls *Patient Details Component* for directing users to its view. The application also has a route guard called *AuthGuard*. *AuthGuard* is responsible for determining whether *AppRoutingModule* should allow navigation to a view or not. It checks whether there exists a non-expired user token, which is a JSON formatted user authentication data, generated by *Firebase Authentication* through the login of a user. If not, it does not allow the navigation to any of the views through url and it directs users to the *Login View*.

Within the scope of this thesis, it is planned to evaluate this system with physiotherapists and their patients both from Germany and Turkey. Therefore, the application provides two different language options: German and English. To enable this, the application uses the *ngx-translate*[11]library, which is an internationalization (i18n) library for Angular.

7.3.1. Login View

The first view of the application is the *Login View*. Users as patients or physiotherapists can log in to the system through this view. It consists of a card in the middle of the screen, which contains a common login structure including two input areas: one for an email address, and one for the password. To log in, users should provide their email address and password, which they have used to sign up to the system, and click the "Login" button.

As mentioned in the System Architecture chapter, the application uses *Firebase Authentication* for authentication and authorization of users. Once the user enters his credentials and clicks the "Login" button, *Login Component* calls the *AuthService* that is responsible fror authentication. *AuthService* uses the *AngularFire*[12] library (official Angular library

[11]`https://github.com/ngx-translate/core`
[12]`https://github.com/angular/angularfire`

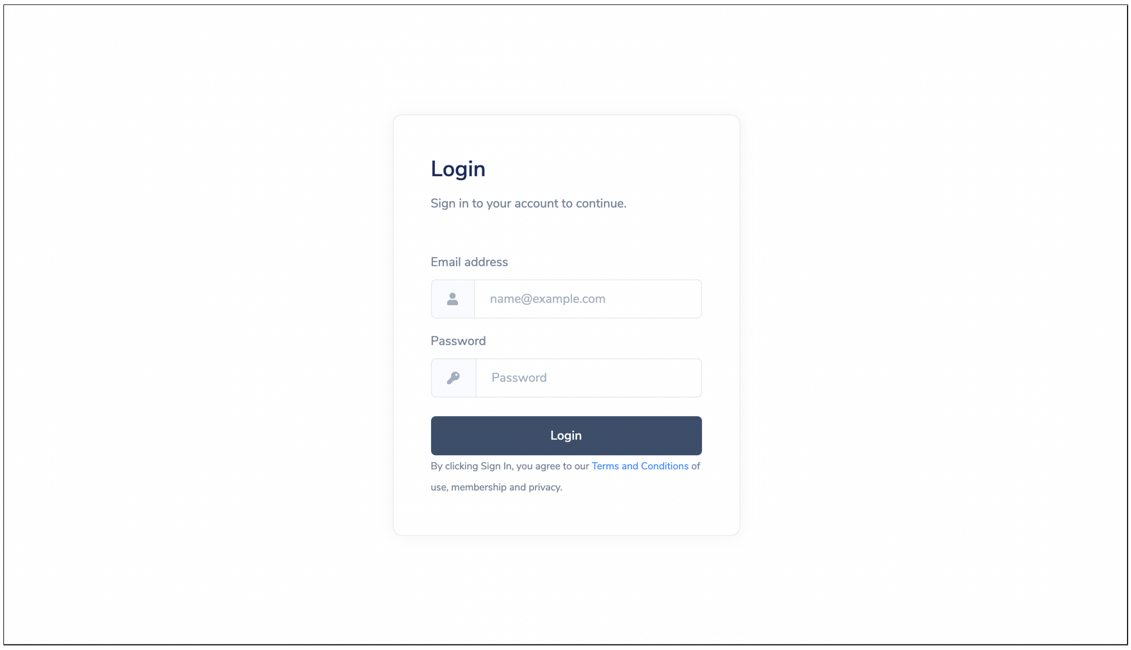

Figure 7.6.: Login View

for Firebase). Through this library, it sends a request to the *Firebase Authentication* component with the user's credentials including the email address and password. If these credentials do not match any of the authorized users in the *Firebase Authentication* component, it returns an error message that is displayed to the user as a reason why the user could not log in to the system. On the other hand, if the credentials match an authorized user in the *Firebase Authentication* component, it returns a user token, and the system logs in the user. The returned token enables the user to stay logged in until the token's expiration time. It also provides data including user credentials. With this data, *AuthService* also sends a request to the *Cloud Firestore Database* to access this user's data that is stored in the *Users Collection*. Through the *role* attribute data of the user inside the user's document in *Users Collection*, the application directs the user to the Patient User Interface (*Patient View*) or the Physiotherapist User Interface (*Physiotherapist View*) depending on the user's role. The application also includes his *user id* as a parameter in the directed url.

7.3.2. Patient User Interface

Patient View

Once patients log in to the web application through the *Login View*, the application directs them to the *Patient View* of the Patient User Interface. To personalize this view, the *Patient Component* gets the id of the patient from the parameter of the url and calls the *UserService*, which sends a request to the *Cloud Firestore Database* to get the patient's

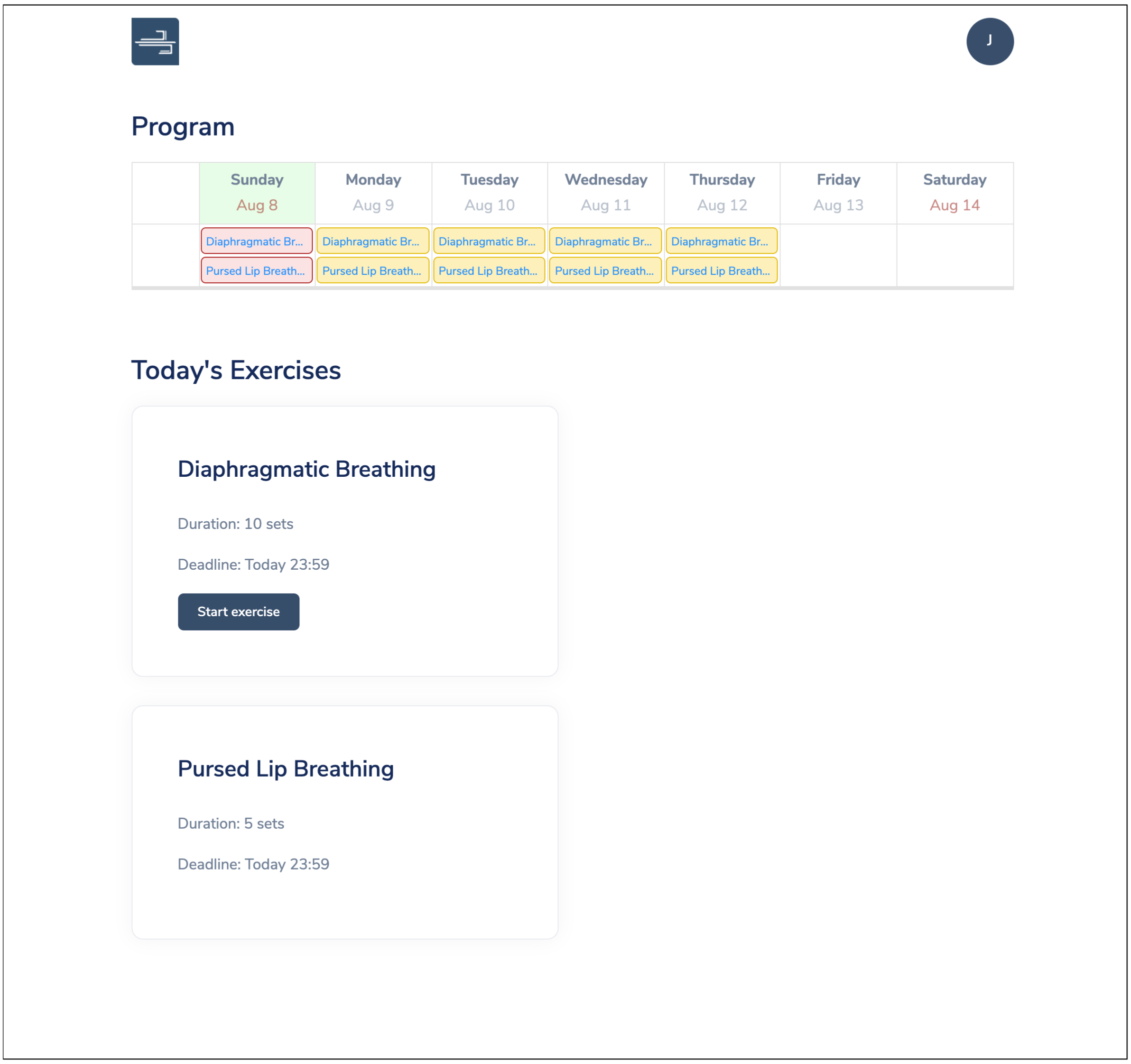

Figure 7.7.: Patient View

data. With the retrieved patient data, *Patient Component* sequentially calls *ExerciseService* to retrieve exercise data, and create the exercise program to display it on a weekly calendar view.

- **Calendar for patient exercise program:**
  Patient Component uses *angular-calendar*[13], which is a calendar library for Angular versions 6.0 and above. It provides a built-in calendar component that has optional monthly, weekly, and daily calendar views. It takes multiple inputs such as view date, events in a specific format, the language of the calendar, and event handlers that call functions on an action event. For the *Patient View* of our application, this calendar is used to display patients their exercise program including their assigned

[13]https://angular-calendar.com/

exercises on each day on a weekly view. These exercises are labeled in green, red, or yellow for informing them respectively whether they have done their exercise or not, or the exercise is on a further date.

If the patient has an assigned exercise on that day, *Patient View* displays him the assigned exercises for that day under the calendar view. Each assigned exercise for that day is shown in the performing order on a card, where the title, duration, and deadline of the exercise are displayed to the user. If the assigned exercises are not yet done, the patient can start the exercise by clicking the "Start exercise" button on the card of the first assigned exercise.

Before and after performing the exercises on a day, the patient has to answer questions regarding his health status on that day. This is for assessing the patient's exertion and shortness of breath and evaluating his RPE scale evaluation for determining his well-being.

- **Well-being questionnaire:**
  Once the patient clicks the "Start exercise" button, as well as once all the assigned exercises for that day are performed, the *Patient Component* pops up a window and calls *Survey Component*, as Figures 7.8 and 7.9 illustrate. On the popup window, *Survey Component* displays a questionnaire where users need to answer multiple-choice questions. *Patient Component* provides the survey type as an input to the *Survey Component*, clarifying whether it is a before or after exercise questionnaire. Then, *Survey Component* calls *GeneralService* with the survey type and language parameters to retrieve the questions from a local file and displays them. At the end of the questionnaire, *Survey Component* provides all the answers of the patient to the *Patient Component*.

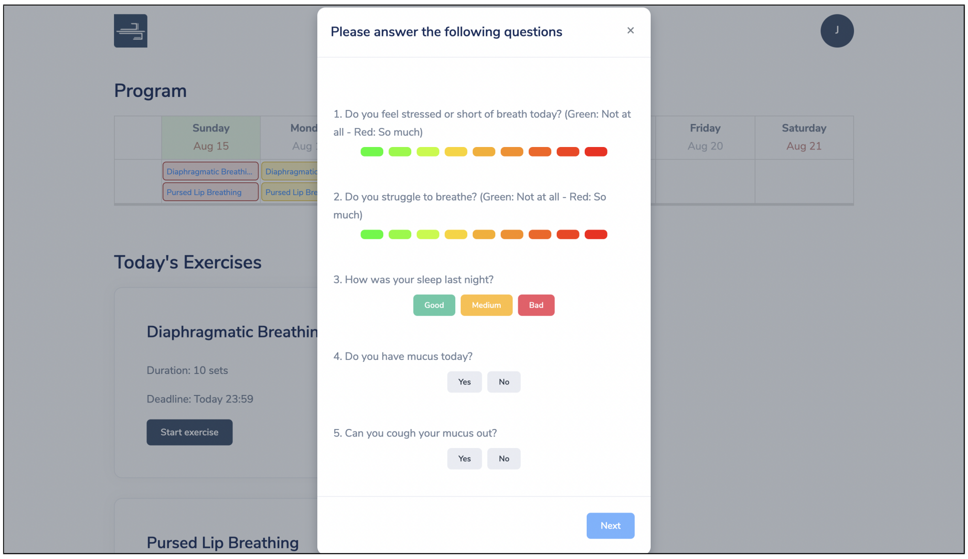

Figure 7.8.: Before-exercise questionnaire

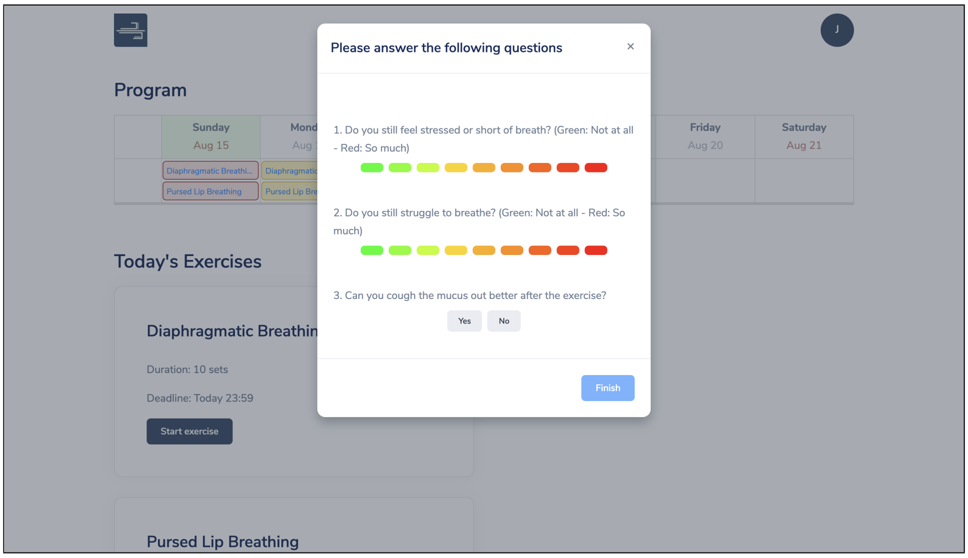

Figure 7.9.: After-exercise questionnaire

Exercise View

When the patient finishes the before-exercise questionnaire and clicks the "Next" button, the *Patient Component* directs the patient to *Exercise View* by calling *Exercise Component* and providing the exercise type as an input. This input contains exercise data including instructions, as well as the customized duration of instructions for the individual patient. *Exercise Component* calls *VideoService* that requests general explanatory video on how to use the application, and exercise specific explanatory video from *Cloud Storage* by using *AngularFire* library. On the *Exercise View*, these videos are displayed on top of the screen on a video frame using an HTML video tag before the exercise starts. Next, *VideoService* sends another request to *Cloud Storage* for retrieving the audio instructions as well. For both requests, *VideoService* also includes a language parameter for retrieving the files considering the usage language of the application.

- **WebRTC Approach:**
  For the monitoring and analysis of patient's exercise performance, the application uses the WebRTC approach. WebRTC is an open-source framework that enables developers to add Real-Time Communications (RTC) to their applications.[14] These Real-Time Communications can support basic operations, e.g. accessing data from web camera, to complex services that provide video call solutions. In our research, the WebRTC approach is used for initializing the client's camera, getting image frames from the real-time video stream, sending these image frames to the *Flask Web Server*, and displaying the returned images on the patient's screen.

  Exercise Component initializes the web camera of the patient's computer by using

[14] `https://webrtc.org/`

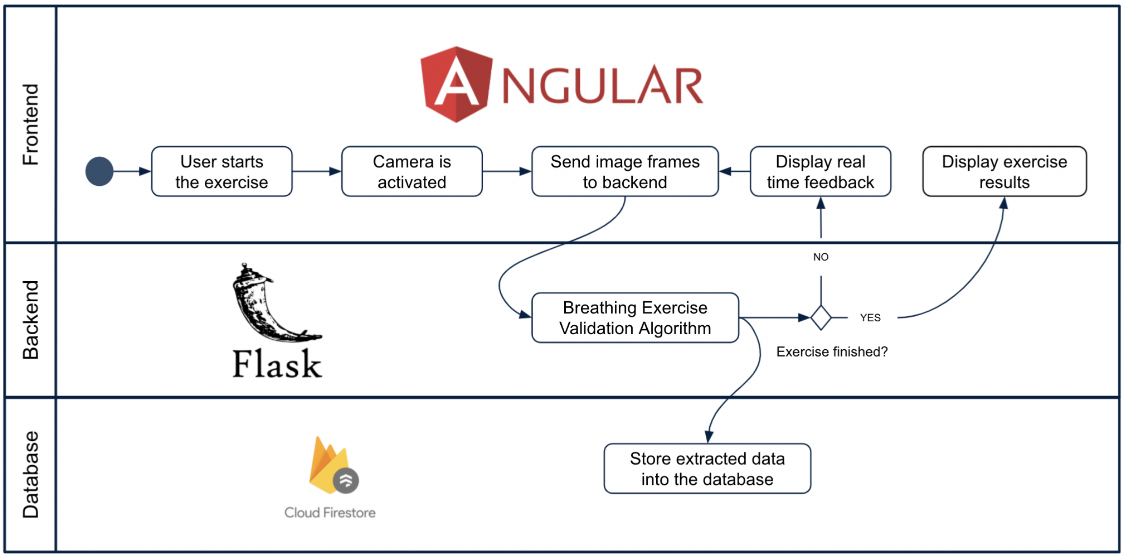

Figure 7.10.: WebRTC approach system architecture

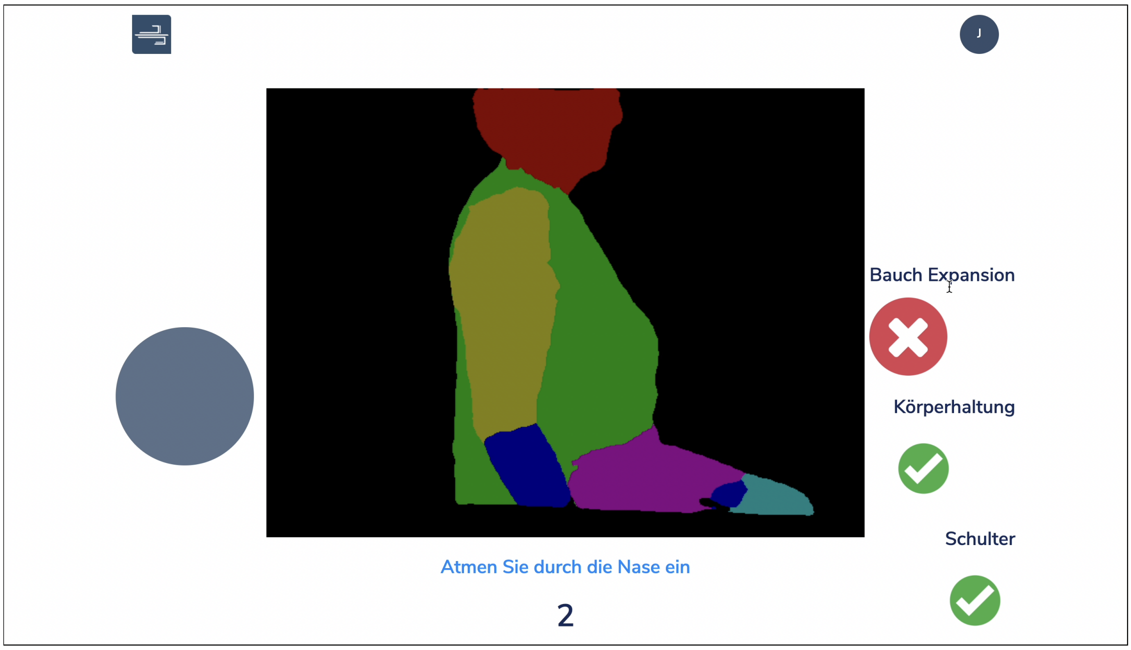

Figure 7.11.: Exercise View while patient is performing an exercise

WebRTC's getUserMedia() to access the media device (web-camera) of the patient's computer and displays the real-time video on the HTML video tag. When the patient starts the exercise by clicking the "Start" button below the real-time mirror view, *Exercise Component* separates the video stream into image frames and calls *VideoService*, sending an image frame as an input. Then, *VideoService* sends a request and forwards this image frame to the endpoint that contains the Computer Vision algorithm. Once the algorithm analyzes the image frame, divides it to the body segments in different colors, and returns the colored image, *Exercise Component* puts this image to the canvas frame, which replaces the HTML video tag. *Exercise Component* calls the *VideoService* with the next image frame as soon as the previous request returns the colored image. This process continues until the end of the exercise.

In the meantime, the *Exercise Component* displays instructions of the exercise, as well as playing the audio instructions on the *Exercise View*. At the end of the duration of each instruction, *Exercise Component* calls *VideoService*, which sends a request to another endpoint for retrieving the detection results of the previously monitored instruction, considering the three proper breathing pattern metrics. These results, which contain *belly expansion*, *shoulder increase*, and *body posture*, are displayed to the patient on the right side of the screen as real-time feedback. Tick icon corresponds to the correctly performed metric, and cross icon corresponds to the wrongly performed metric. Figure 7.10 illustrates how this approach works between the different components of the system. Figure 7.11 shows the *Exercise View* while a patient is performing an exercise.

During the exercise performance, *Exercise Component* also provides basic gamification of an expanding and contracting circle, which moves aligned with the inhale and exhale instructions. It is displayed on the left side of the *Exercise View*.

7.3.3. Physiotherapist User Interface

Physiotherapist View

When physiotherapists log in to the web application through the *Login View*, the application directs them to the *Physiotherapist View* of the Physiotherapist User Interface. Similar to the Patient User Interface, to personalize *Physiotherapist View*, the *Physiotherapist Component* gets the id of the physiotherapist from the parameter of the url and calls the *UserService*, which sends a request to the *Cloud Firestore Database* to get the physiotherapist's data. Using this physiotherapist data, the *Physiotherapist Component* calls the *UserService* once again to retrieve all the patients, who are treated by this physiotherapist through the application. Finally, it also calls the *ExerciseService* to retrieve all the exercises, which physiotherapist has on the application to be assigned to his patients.

After retrieving all the data from the *Cloud Firestore Database* for personalizing the *Physiotherapist View*, the *Physiotherapist Component* displays all this data on the *Physio-*

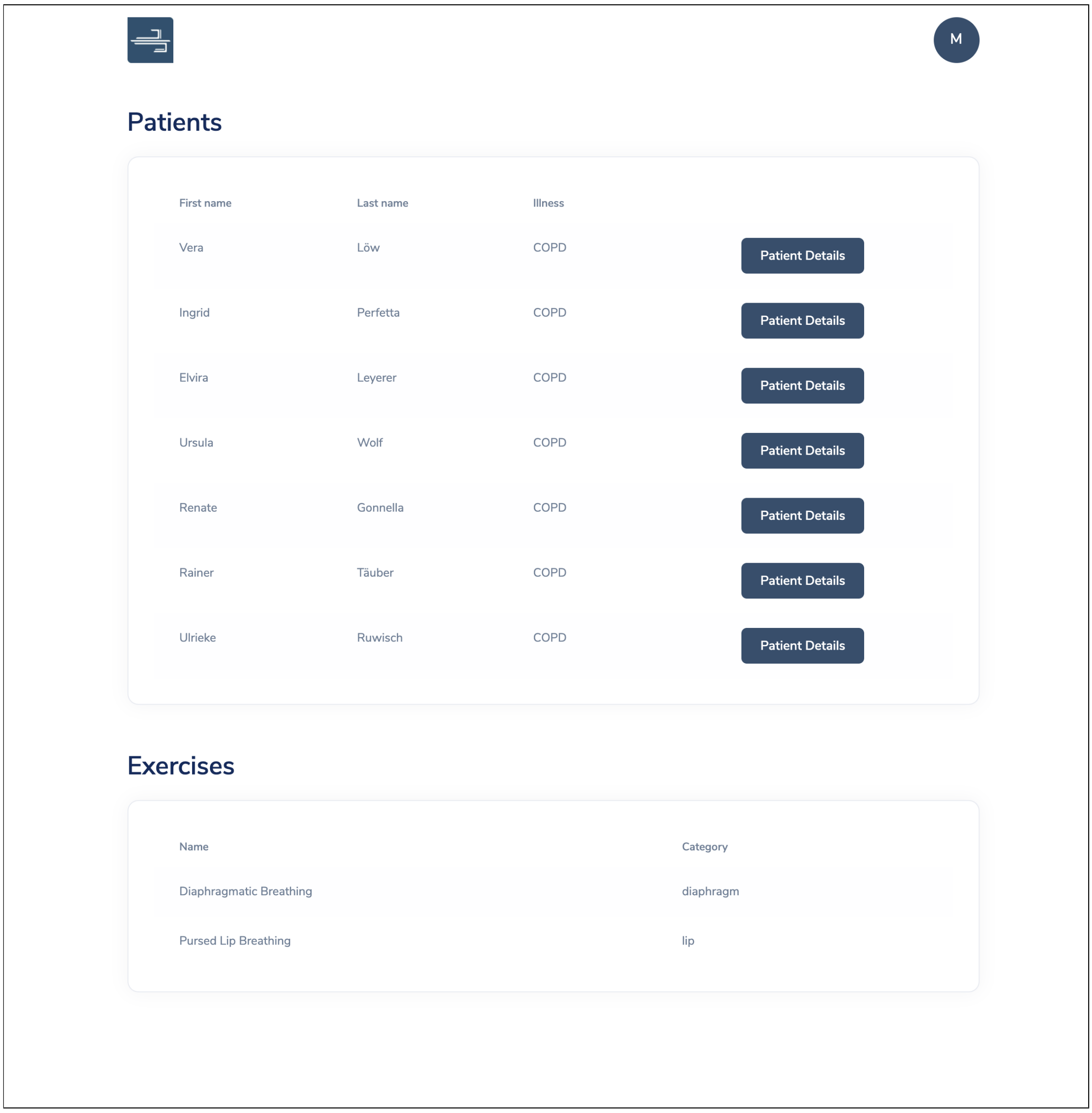

Figure 7.12.: Physiotherapist View

therapist View. On top of this view, a list consisting of physiotherapist's all patients are displayed on a card. The information of each patient on the list consists of the first and last names of the patient, as well as his illness. Next to each patient on the list, there is a button called "Patient Details" which directs the physiotherapist to the *Patient Details View* of the selected patient. Below this card containing the list of patients, *Physiotherapist View* also provides another card that contains the list of the physiotherapist's all available exercises. In this card, the physiotherapist can see the name and category of each available exercise. *Physiotherapist View* can be seen in Figure 7.12.

Patient Details View

When physiotherapists would like to see the detailed home exercise performance and well-being of individual patients, they can click on the "Patient Details" button, which is on the right side of each patient row, on the patients list. This button directs the physiotherapist to the *Patient Details View*, where they can see a detailed analysis of the selected patient's exercise performance and well-being. While directing the physiotherapist to the *Patient Details View*, the *Physiotherapist Component* also passes the selected patient data and physiotherapist's available exercise list to the *Patient Details Component* as an input. Using the patient data input, the *Patient Details Component* calls the *ExerciseService*, which sends a request to the *Cloud Firestore Database* to retrieve the details of the patient's exercises.

Patient Details View maintains a weekly calendar view for the exercise program of the selected patient on top of the view, similar to *Patient View*. Below the calendar view, it provides two columns. The left column displays the assigned exercises to the patient, as well as enables the physiotherapist to edit these exercises, and assign new exercises. The right column provides general information about the patient, including his name and illness. Figure 7.13 shows a screenshot of the *Patient Details View*.

- **Calendar for patient exercise program:**
  Similar to the *Patient View*, *Patient Details View* also uses the *angular-calendar* library for displaying the exercise program of the selected patient on a weekly calendar. This calendar is used for displaying the physiotherapist an overview of the patient's exercise performance, on determining whether the patient has done his assigned home exercises or not. Different from the *Patient View*, *Patient Details View* provides an additional popup feature on this calendar. In addition to the inputs provided to the *angular-calendar* library such as view date, events, and language, the *Patient Details Component* also provides an input of event handler that calls a function on an action event. With this input, the calendar opens a popup window when the physiotherapist clicks on a specific exercise on the calendar. This popup window can be seen in Figure 7.14

  On top of the view, the popup window displays the answers of the patient to the before and after-exercise questionnaires on the chosen date. These answers are displayed in two columns: the left column for the answers to the before-exercise questionnaire, and the right column for the answers to the after-exercise questionnaire. This enables the physiotherapist to easily compare the well-being results of the patient before and after the exercise to determine the efficiency and the effects of the exercise. For each column, the scale evaluation of the patient's well-being is also calculated and displayed. To align it with the actual treatment and to ease the understanding of the physiotherapist, this scale evaluation is shown within a label in green, yellow, or red colors. Below the questionnaire results, the popup window also displays the results of the patient's performance on the chosen exercise. These results are evaluated separately for the inhale and

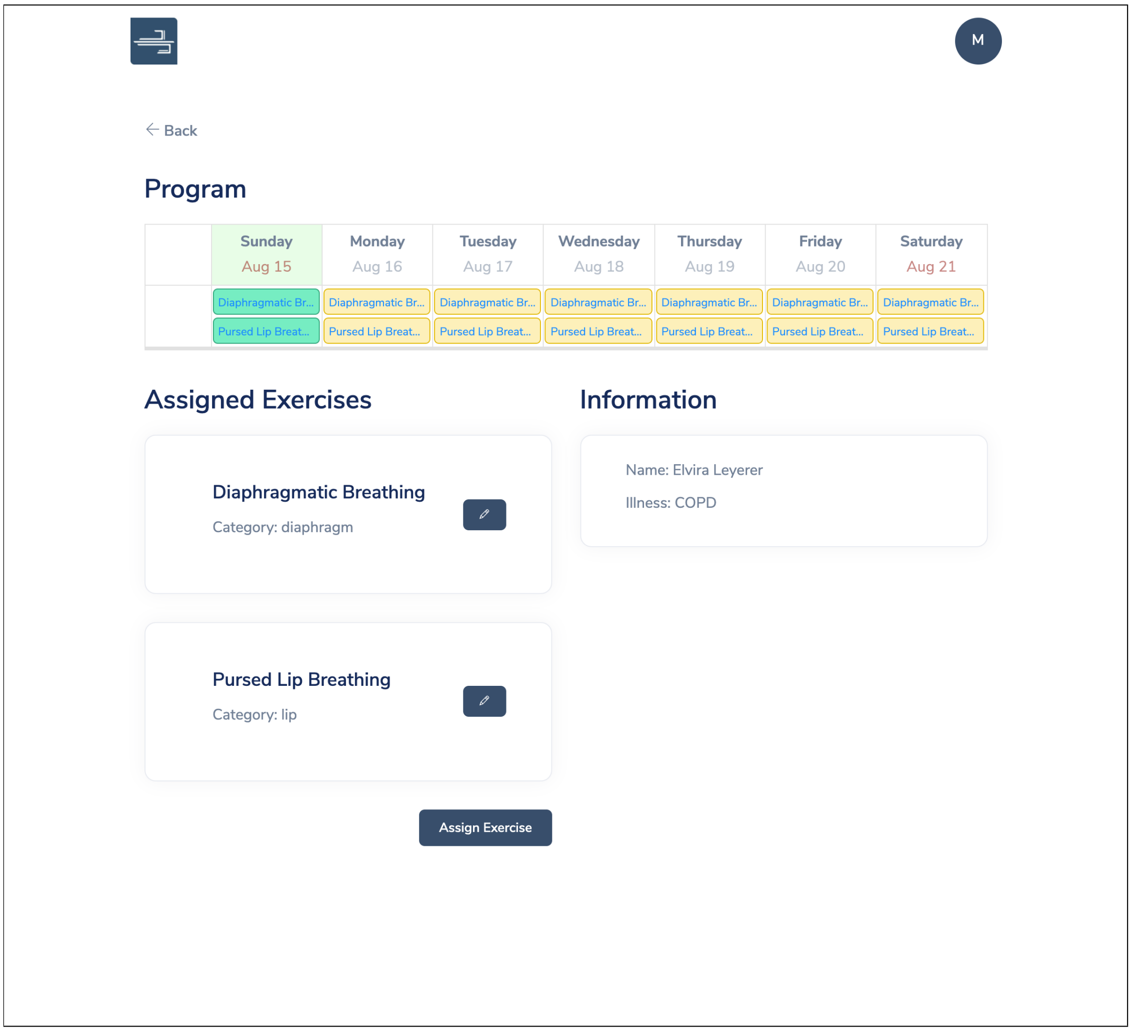

Figure 7.13.: Patient Details View

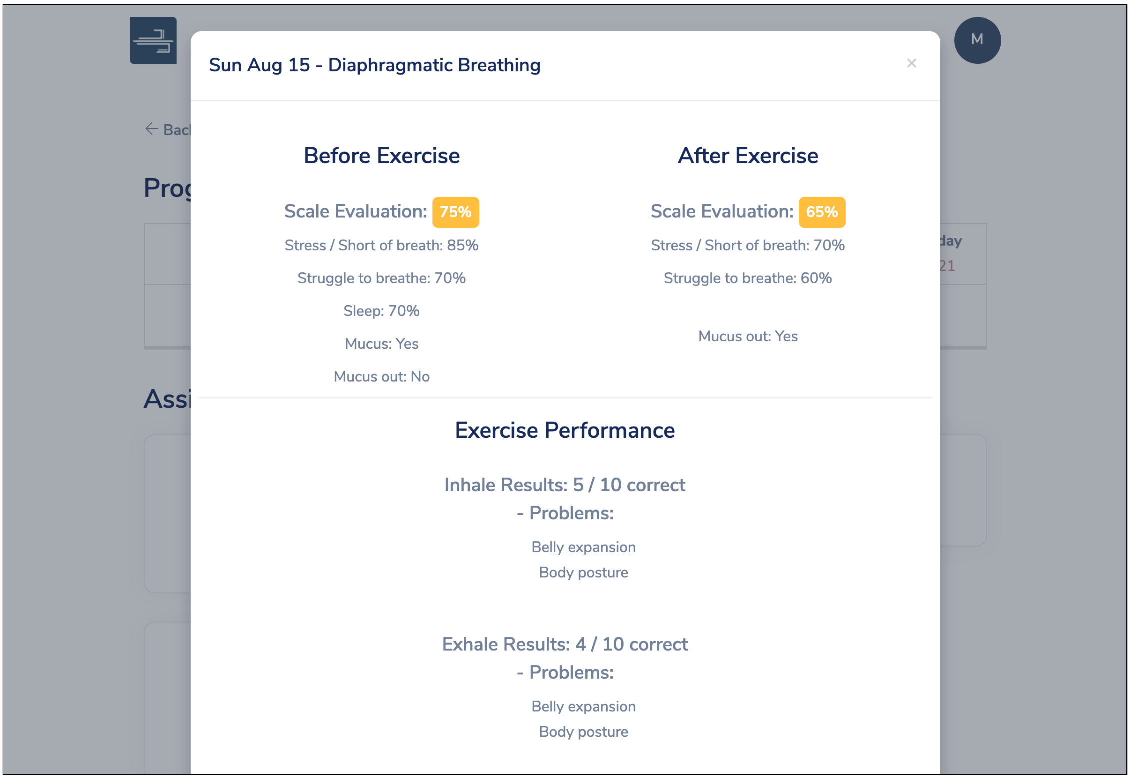

Figure 7.14.: Patient Exercise Performance Details View

exhale performances. In other words, the view displays the physiotherapist how many of the inhale results the patient performed correctly, as well as how many of the exhale results the patient performed correctly. The reason for this separation is to clarify which of the main commands the patient is struggling with. In addition to the overall performance on both commands, the view also displays whether the patient had problems on any of the specific metrics. To prevent false negatives, the *Patient Details Component* checks whether a problem occurred more than 1 time before displaying it. This can be seen as a tolerance of the application.

- **Customization and assignment of exercises:**
  Patient Details Component enables physiotherapists to customize and assign exercises to a patient as mentioned above. If the patient has assigned exercises, they are displayed inside cards under the "Assigned Exercises" title on the *Patient Details View*. When the physiotherapist clicks on the "Assign Exercise" button below these cards, the *Patient Details Component* creates a popup window as shown in Figure 7.15. This popup window has a dropdown button, where the physiotherapist can choose the exercise that he wants to assign to the patient from a list of all the available exercises. *Patient Details Component* compares the list of the physiotherapist's all exercises with the list of already assigned exercises of the patient, to determine the available exercises which can be assigned to him. The popup window has

two more input fields where the physiotherapist needs to provide the instruction duration for both inhale and exhale commands. Since this duration is chosen only for an individual patient instead of all patients, it provides customization for the individual patient. *Patient Details Component* also enables the physiotherapist to edit and change these durations from the main *Patient Details View* by clicking on the button with a pencil icon inside each assigned exercise card.

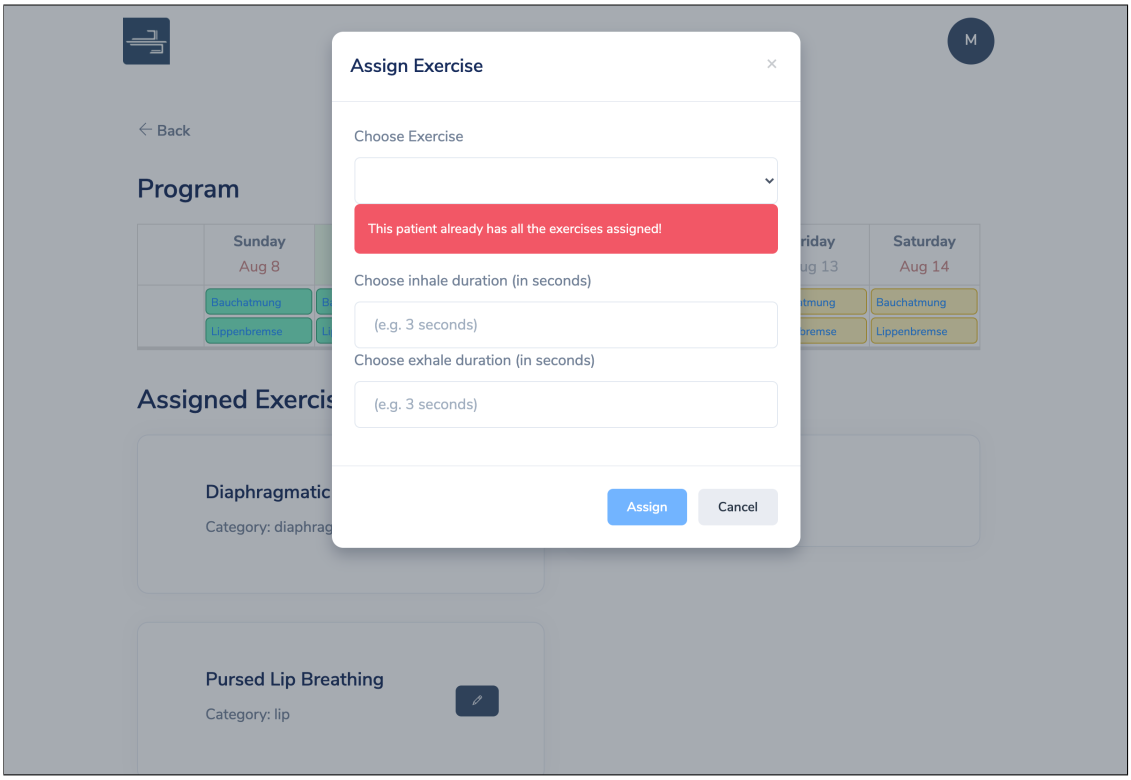

Figure 7.15.: Customization and assignment of exercises

8. Evaluation

This chapter describes the evaluation of the solution that is implemented in the scope of this thesis. It elaborates on the participants and the process of the evaluation, as well as the results, and provides answers to *RQ3: From the perspective of physiotherapists, how does this approach improve the efficiency of the COPD treatment?* and *RQ4: How usable is this approach in the treatment of COPD from the perspectives of patients and physiotherapists?*

8.1. Evaluation Approach

In the scope of this thesis, the evaluation approach consists of two goals. The first goal is to evaluate the quality and performance of the implemented system. This includes evaluating the accuracy of the Computer Vision algorithm that detects the proper breathing pattern, and efficiency of using this system in the treatment of COPD. The second goal is to evaluate the usability of the implemented system for both patients and physiotherapists. Therefore, the evaluation process is divided into two different phases for addressing these goals.

The first phase is the accuracy evaluation of the Computer Vision algorithm for detecting the proper breathing pattern. This evaluation phase is conducted at a physiotherapy clinic in Munich, including 2 physiotherapists and 3 patients as shown in Table 8.1.

Table 8.1.: Participants for the breathing pattern detection accuracy evaluation.

No	Role	Age Interval
1	Patient	61-70
2	Patient	61-70
3	Patient	70+
4	Physiotherapist	18-39
5	Physiotherapist	40-50

The method that is used for this evaluation is the comparison of the results of a physiotherapist and our system on a person's exercise performance. For this, all 5 participants are individually asked to use the system for performing an exercise, while a physiotherapist is observing the participant without being capable of seeing the system's results. The physiotherapist, who is observing the participant's exercise performance, is asked to note down the exercise performance of the participant on each instruction based on the tree proper breathing metrics, namely belly expansion, shoulder increase, and body posture. In the meantime, the performance of the participant is recorded as a movie screening of the used computer to capture the system's exercise performance results. Another video of the participant is also taken from the point of view of the physiotherapist, in case she would like to review the movement of the participant's body to determine the proper breathing pattern. Finally, the results of the physiotherapist and the system, based on the participant's exercise performance, are compared to evaluate the breathing pattern detection accuracy.

The second phase consists of the usability and efficiency evaluation of this system for both patients and physiotherapists in the treatment of COPD. This evaluation phase is conducted with 4 physiotherapists and 5 patients from Germany and Turkey as shown in Tables 8.2 and 8.3.

Table 8.2.: Physiotherapists that participated in the usability evaluation.

No	Age Interval	Professional Experience	Nationality
1	18-39	3-5 years	German
2	40-50	10+ years	German
3	51-60	10+ years	German
4	18-39	3-5 years	Turkish

Table 8.3.: Patients that participated in the usability evaluation.

No	Age Interval	Illness Duration	Nationality
1	61-70	6-9 years	German
2	61-70	10+ years	German
3	70+	6-9 years	German
4	70+	10+ years	German
5	51-60	0-2 years	Turkish

For this evaluation, all 4 physiotherapist participants are asked to integrate this system into the treatment of their COPD patients for a period of two weeks. Two different exercises, including one diaphragmatic breathing exercise and one pursed lip breathing exercise, are assigned to every patient to be performed daily as a two weeks exercise program. Physiotherapists are asked to customize the duration of the inhale and exhale instructions of these exercises for their individual patients, and check their patients' exercise performance and well-being regularly through the system. To motivate them on checking the application regularly, the system allows the physiotherapists to only see the exercise performance of their patients on a weekly view. On the other hand, with the integration of this system to their treatment, the 5 patient participants are asked to perform their daily exercises on the system alongside with their one-on-one physiotherapy sessions at the clinic. At the end of this two weeks testing period, all participants are asked to evaluate the usability of the system through System Usability Scale (SUS). Besides the SUS, patients and physiotherapists are also asked separate questions and statements to evaluate the efficiency of this system in the treatment of COPD.

8.2. Breathing Pattern Detection Accuracy

As described in the previous section, the accuracy of the Computer Vision algorithm of the system that detects the proper breathing pattern is evaluated through the comparison of the physiotherapist's and the system's results based on a participant's exercise performance. The accuracy is evaluated with the following formula:

$$Accuracy(\%) = \frac{TP + TN}{TP + TN + FP + FN} \times 100$$

where:

- TP (true positive) is the number of metrics that are accurately detected by the system, and performed correctly
- TN (true negative) is the number of metrics that are accurately detected by the system, and performed incorrectly
- FP (false positive) is the number of metrics that are inaccurately detected by the system, and performed incorrectly
- FN (false negative) is the number of metrics that are inaccurately detected by the system, and performed correctly

Table 8.4.: Average accuracy evaluation of each breathing pattern metric detection.

Detection \Exercise	**Diaphragmatic Breathing Exercise**	**Pursed Lip Breathing Exercise**
Belly Expansion	83%	80%
Shoulder Increase	92%	85%
Body Posture	97%	92%
Overall	90.6%	85.6%

The results are calculated separately for each participant's performance on the two different exercise types (*Diaphragmatic Breathing Exercise* and *Pursed Lip Breathing Exercise*). They are summarized and displayed in Table 8.4 by combining and calculating the average accuracy of all participants. The results show that the algorithm has different accuracy results for the two different types of exercises.

The overall detection accuracy for the *Diaphragmatic Breathing Exercise* is **90.6%**, having respectively 83%, 92% and 97% for the "belly expansion", "shoulder increase", and "body posture" detections.

For the *Pursed Lip Breathing Exercise*, the overall detection accuracy is **85.6%**, having sequentially 80%, 85% and 92% for the "belly expansion", "shoulder increase", and "body posture" detections.

8.3. Evaluation of the system (RQ3 and RQ4)

8.3.1. Usability Assessment based on the System Usability Scale

For the usability evaluation of our implemented system, our evaluation approach uses System Usability Scale (SUS) that is developed by John Brooke [14]. It uses a scale that consists of 10 simple questions for assessing the usability of a system by its participants of a user group. The questions of the SUS are designed for assessing the effectiveness, efficiency, and satisfaction of users while using the system [14]. Their answers are on a scale of 1 to 5, 1 meaning that the participant strongly disagrees with the statement of the question, and 5 meaning that the participant strongly agrees with it. The calculation of the evaluation score between 0-100, based on participant's answers are described by John Brooke as follows: *"To calculate the SUS score, first sum the score contributions from each item. Each item's score contribution will range from 0 to 4. For items 1,3,5,7,and 9 the score contribution is the scale position minus 1. For items 2,4,6,8 and 10, the contribution is 5 minus the scale position. Multiply the sum of the scores by 2.5 to obtain the overall value of SU"* [14].

Although the SUS Score provides a usability evaluation score between 0-100 for the system as a relative judgement [15], the translation of this score into a qualitative judgement was unclear. To address this missing point, Aaron Bangor et. al provide a method of adding an adjective rating scale to the SUS, which provides a qualitative judgement translation of the SUS score [15]. Figure 8.1 illustrates an example comparison of SUS score with the translated acceptability ranges, grade scale, and adjective ratings [15].

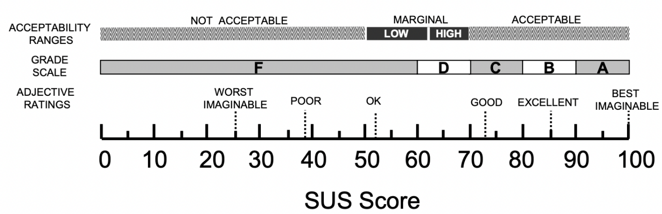

Figure 8.1.: A comparison of SUS score with acceptability ranges, grade scale, and adjective ratings by Bangor [15]

Table 8.5.: System Usability Score results

No.	Role	System Usability Score	Role	System Usability Score
1	Patient	77.5	Physiotherapist	85
2	Patient	60	Physiotherapist	87.5
3	Patient	67.5	Physiotherapist	85
4	Patient	90	Physiotherapist	95
5	Patient	77.5		
Average		74.5		88.12

Table 8.5 shows the results of the usability assessment from patient and physiotherapist participants. The average SUS score of all five patients is **74.5**, which is in the "Acceptable" range. It has a grade scale of "C", and is at the border of "Good" on the adjective rating scale.

On the other hand, the average SUS score of all four physiotherapists is **88.12**, which is also in the "Acceptable" range. It has a grade scale of "B", and is between "Excellent" and "Best imaginable" on the adjective rating scale.

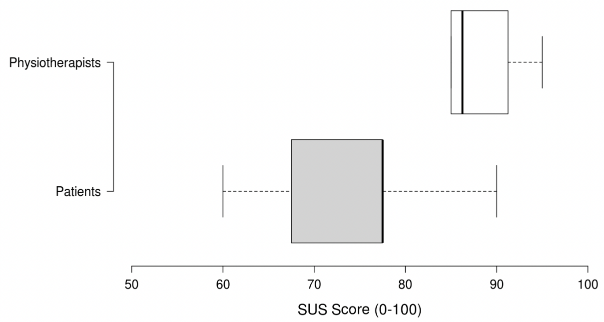

Figure 8.2.: SUS scores for patients and physiotherapists

Figure 8.2 shows the box-plots created with the System Usability score results of patients and physiotherapists.

The highest score of a patient is 90 and the lowest score of a patient is 60. The upper quartile is 77.5, whereas the lower quartile is 67.5. The median of the patients' SUS score is 77.5. These results show that the usability of the system is acceptable for the patients. However, there is certainly a potential for improvements to make the usability better.

The highest score of a physiotherapist is 95 and the lowest score of a physiotherapist is 85. The upper quartile is 91.25, whereas the lower quartile is 85. The median of the physiotherapists' SUS score is 86.25. These results show that the physiotherapists are more satisfied than the patients with the usability of this system. Nevertheless, the usability can still be improved with further developments.

8.3.2. Assessment of the System's Efficiency and Main Goals

To assess the efficiency of the system and determine whether the system achieved the main goals for patients and physiotherapists in the treatment of COPD, the patient and physiotherapist participants are separately asked questions and statements about their experience of using this system in their treatment for two weeks.

Evaluation of Patients

Questions for patients on the assessment of the system's efficiency and main goals focused on the comparison of their motivation for doing their exercises, health status, and treatment process with and without this system.

- **Question 1:** How often did you do your home exercises before this system?
- **Question 2:** How often did you do your home exercises using this system?

These two questions aim to assess whether having such a system affects the frequency of performing these exercises. Figure 8.3 displays the answers of five patients to *Question 1* and *Question 2*. It shows that with the integration of this system into their treatment, all the patients either increased or kept the same frequency of doing their home exercises in comparison to before.

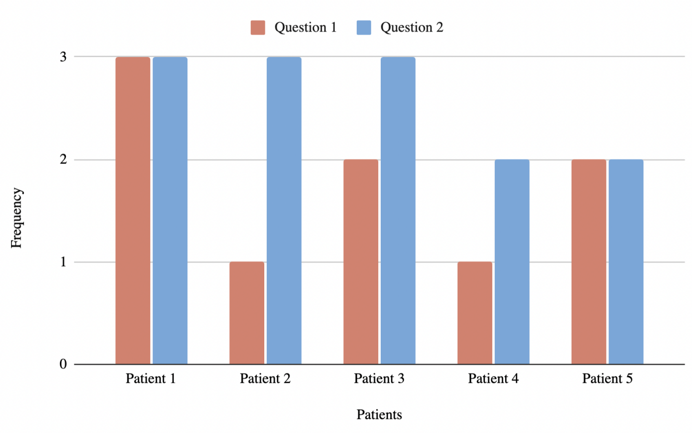

Figure 8.3.: Evaluation results for Question 1 and Question 2

- **Statement 1:** This system increased my motivation for doing my home exercises.
- **Statement 2:** This system helped to improve my health condition.
- **Statement 3:** I would like to use this system in my treatment.

Different than the previous two questions that assess the system with a fact, these three statements aim to assess the system's effects on patients through their opinion about it. Figure 8.4 illustrate the individual results for *Statement 1, Statement 2 and Statement 3*. The results show that for the *Statement 1* and *Statement 2*, the patients have different opinions. However, for the *Statement 3*, all of the patients are either positive or neutral about integrating this system into their treatment.

Evaluation of Physiotherapists

Two statements are asked to the physiotherapists to aim the assessment of the efficiency of using this system on their treatment process.

- **Statement 1:** This system increased the efficiency of the treatment.
- **Statement 2:** I would like to use this system for the treatment process.

These two statements aim to assess whether this system increases the efficiency of the treatment, as well as whether physiotherapists would like to use this system on their treatment process. Figure 8.5 displays the answers of four physiotherapists to *Statement 1* and *Statement 2*. For the *Statement 1*, the results show that 25% of the physiotherapists strongly agrees that the system increased the efficiency of the treatment, whereas 50% are neutral and 25% disagrees with it. For the *Statement 2*, 75% of the physiotherapists agrees that they would like to use this system for the treatment process, whereas 25% disagrees.

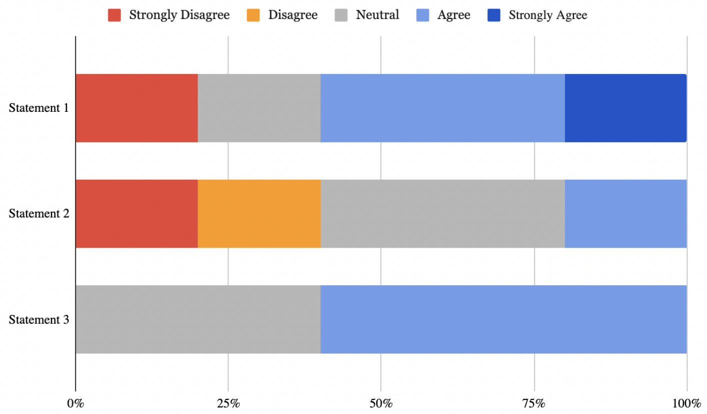

Figure 8.4.: Patient evaluation results for Statement 1, Statement 2 and Statement 3

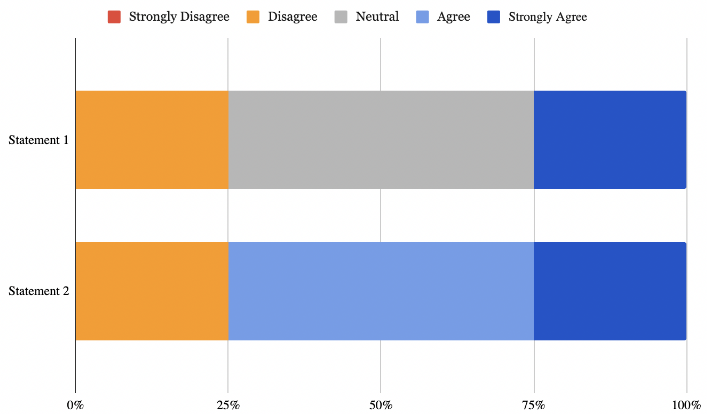

Figure 8.5.: Physiotherapist evaluation results for Statement 1 and Statement 2

9. Discussion

This chapter describes the analysis of the results that are explained in the previous chapter. It also tells about the limitations of the system in terms of internal and external effects.

9.1. Result Analysis

The results of the evaluation can be considered in two segments considering the two evaluation approaches for assessing the accuracy of the breathing pattern detection, and usability and efficiency of the system.

First of all, the accuracy of the algorithm that detects the proper breathing pattern is relatively high. The accuracy evaluation results indicate the potential of this system for clinical use cases in terms of its technology. Moreover, the accuracy results are also promising that the accuracy can be improved to have a much higher rate with further developments on the algorithm.

Secondly, the usability and efficiency assessment results show that the system can make COPD treatment more effective for patients. Although two weeks of testing time is short for determining whether using this system improves the health condition of patients, the results show that all patients either increased or kept the same frequency of doing their home exercises with the integration of this system into their treatment. This demonstrates that the system increases the motivation of the patients for doing their home exercises, thus serves to address the lack of motivation problem of this treatment. Furthermore, 60% of the patients stated that they would like to use this system in their treatment. This clarifies the interest of patients in integrating this system into their treatment process.

On the other hand, physiotherapists have different opinions on the efficiency of this system. According to the evaluation results, all physiotherapists agree that such a system increases the efficiency of COPD treatment for the patients since they have a motivating system that accompanies them while performing their exercises at home. However, their thoughts differentiate on whether this system would increase the efficiency for the physiotherapists in the treatment process. Even though they have doubts about the efficiency of this system for physiotherapists, the results show that 75% of them would like to use this system with their patients in their treatment process. Hence, this shows that with improvements on the system for creating more added values for the physiotherapists, it can be more attractive for them since there already is an interest.

9.2. Limitations

In the scope of this thesis, there have been limitations in terms of the research, as well as the limitations of the implemented system. To begin with, the first limitation is the time schedule for the evaluation of this thesis. Since the implemented system aims to address the respiratory physiotherapy treatment of COPD patients, the time frame for the evaluation is very limited for determining proper evaluation results based on medical assessments. Respiratory physiotherapy treatment lasts between 6 to 10 weeks in Germany[1], whereas the evaluation of the implemented system with patients and physiotherapists is scheduled for only 2 weeks. Therefore, the qualitative evaluation of the efficiency of the system is limited because of the short time frame.

In addition to the limitations of the research, the limitations of the system can be examined within internal and external validities.

9.2.1. Internal Validity

The biggest limitation of the system comes from the Pascal-Person-Parts model, which is used in the Computer Vision algorithm for separating the patient's body from the rest of the image and dividing the body into body segments. The algorithm, which detects the proper breathing pattern, uses the output image that is provided by this machine learning model. Therefore, the detections that are provided by the system always depend on the output of this machine learning model. In other words, if the Pascal-Person-Parts model does not work properly, and divide the body into correct body parts, the system will not provide a correct detection. For instance, if the patient's clothes have a similar color with the background, the Pascal-Person-Parts model might have errors on detecting the patient's body parts, thus the system would process incorrect body parts for the breathing pattern detection. This would lead to inaccurate results.

Furthermore, the system provides instructions for the breathing exercise and monitors the patients at the same time for providing feedback based on their performance. For the system to provide correct results, it is very significant that the patient performs the exercise aligned with the instructions. The system provides explanatory videos before the exercise to inform the patient about the instructions of the exercise that they will start performing in advance. Nevertheless, some patients stated that they can not align with the instructions as they wait for the audio command to finish to perform that specific instruction. In this case, this can be considered as another limitation of the system.

9.2.2. External Validity

The research of this thesis is conducted based on respiratory physiotherapy treatment in Germany and Turkey. The system is implemented considering the requirements collected

[1] 12B. . P., GmbH, B. u. P. (2020). Heilmittel-Richtlinie und Heilmittel-Katalog (12. Auflage, revidierte Ausgabe.). Buchner u. Partner.

based on the treatment process in these two countries. The use of the Computer Vision algorithm to detect the proper breathing pattern in the breathing exercises of patients would not cause any limitations in the clinical environments of different countries. Nonetheless, the treatment process for the treatment of COPD may differentiate in other countries for physiotherapists and patients. Therefore, this may cause a limitation for the use of the system in different countries.

10. Conclusion

This chapter summarizes the objectives, research, and results of this thesis. It also describes the suggestions for future work.

10.1. Summary

The goal of this thesis was to develop a web-based system that assists both physiotherapists and their patients in the treatment of COPD. To achieve this goal, the research started with a case study including a survey and expert interviews that are conducted to physiotherapists to understand the respiratory physiotherapy treatment of COPD patients, its challenges, and the breathing exercises within this treatment. The answers of physiotherapists to this survey and on the interviews provided the effective exercises, as well as the relevant and measurable metrics for these exercises in the treatment of COPD. The effective exercises are defined as the pursed lip breathing exercise and diaphragmatic (belly) breathing exercise.

> ***RQ1:*** *What are the relevant and measurable metrics of an effective breathing exercise for the treatment of COPD?*

As an answer to RQ1, the relevant and measurable metrics for these exercises are defined as the belly expansion, shoulder increase, and body posture of patients while performing these exercises.

Through the results of this case study, the functional and non-functional requirements of the system are collected and defined. Moreover, the system's architecture is designed in two components considering the requirements of the system, namely the digital breathing exercise assistant and the digital treatment software.

> ***RQ2:*** *How can an algorithm be developed from the relevant metrics to accurately evaluate the breathing exercise?*

Addressing the RQ2, the implementation of the system started by developing a Computer Vision algorithm that aims to detect the measurable metrics of the effective breathing exercises including the detection of the belly expansion, shoulder increase, and body posture of patients. After the development of this algorithm, the implementation is finalized by the development of the web-based assistive system for both physiotherapists and their patients. Once the implementation is done, the accuracy of the Computer Vision algorithm is evaluated at a clinical setup with 2 physiotherapists and 3 patients.

As an answer to the RQ2, the results of this evaluation showed that the algorithm for the detection of proper breathing pattern metrics provides 90.6% and 85.6% accuracy, respectively for the diaphragmatic breathing and pursed lip breathing exercises.

> ***RQ3:** From the perspective of physiotherapists, how does this approach improve the efficiency of the COPD treatment?*
>
> ***RQ4:** How usable is this approach in the treatment of COPD from the perspectives of patients and physiotherapists?*

For providing answers to RQ3 and RQ4, the implemented system is evaluated in a clinical setup both in Germany and Turkey, including 4 physiotherapists and 5 patients. To evaluate the implemented system in the treatment of COPD, this system is integrated into the actual treatment process of these 4 physiotherapists and their 5 patients. Through this web-based system, the physiotherapists customized and assigned exercises for their patients. While the patients used this system at home every day for performing their exercises with the assistance of the system, the physiotherapists also used it to keep track of their patients' home exercise performance. After the two weeks period, the physiotherapists evaluated the efficiency of this system in the treatment of COPD for answering the RQ3. The physiotherapists have agreed decision on the efficiency of this system for the patients in the treatment of COPD, but their opinions differentiate on the efficiency of this system for themselves. Moreover, both physiotherapists and patients evaluated the usability of this system, through the System Usability Scale survey, to provide an answer to the RQ4. The usability evaluation results showed that this system is usable for both physiotherapists and patients in the treatment of COPD.

10.2. Future Work

The possible future work on this system can be examined in two different segments: the enhancements on the Computer Vision algorithm to increase the detection accuracy for the breathing exercises, and enhancements on the features of the web-based assistive system.

10.2.1. Enhancements on the Computer Vision Algorithm

To increase the accuracy of detecting the proper breathing pattern through the three measurable metrics, the enhancements on the Computer Vision algorithm can be a significant part of the future work. As described in Chapter 9, the biggest limitation of the system comes from the Pascal-Person-Part model which is used in the Computer Vision algorithm since the detection of the algorithm depends on the output image of this model. Therefore, different machine learning models can be studied for differentiating the human body from the rest of the image and parsing the human body into different body parts. In addition to this, other computer vision techniques for image processing can be used rather than the ones that are used in this research.

Moreover, it is also possible to research different approaches than using an already trained machine learning model. Deeper research can be done by training a new model that serves specifically for the purpose of detecting the correct breathing pattern. Since this new model will not depend on another previously trained model but will serve exactly for detecting the breathing pattern, this approach can increase the accuracy of the detections.

10.2.2. Enhancements on the Web-based Assistive System

As the second part of the future work, the web-based system can be enhanced in order to assist physiotherapists and their patients in a more comprehensive way for the treatment of COPD. First of all, the system can be developed as a mobile application to enable the patients to perform their breathing exercises anywhere. Moreover, other exercises can also be added to the system to enhance it for serving patients that are suffering from other respiratory diseases. In this context, the system can be improved to enable the physiotherapists to create new exercises from scratch. This would also enhance the customization and personalization of the exercises on the system.

Furthermore, another significant enhancement of the system for future work would be adding informative content for the patients to increase their awareness about their illness and the treatment process. Besides the information content, the system can provide patients reminders and checklists to increase their motivation, and create a regular regimen in their treatment process.

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A. Appendix

A.1. Structured Interview

1. Personal Information
2. In which institution do you work?
3. What is your role?
4. On average: How many patients are treated in your practice every day?
5. Does it happen that you cannot accept new patients because you are fully booked?
6. How often does it happen weekly that you cannot accept new patients?
7. How high do you estimate the percentage of patients who pay money for extra services?
8. How much does a patient pay on average for extra services per prescription?
9. On average, how many patients do you treat per day?
10. On average, how many minutes do you spend with each patient?
11. How many minutes is your preparation and follow-up time after each patient?
12. What are the three types of treatment that you practice the most?
13. How important is the continuity of physiotherapy treatment in chronic diseases?
14. Would you use digital solutions to improve the continuity of therapy?
15. Would you use digital solutions to improve the duration of therapy?
16. Do you give your patients homework?
17. How important is the patient's own contribution (independent completion of homework) for the success of treatment?
18. Would you use digital solutions that allow you to both care for your patients from home and give you more control over patient services between appointments?
19. What reasons prevent patients from accessing appropriate physical therapy?

20. How important do you think digital solutions are in helping more people reach professional physical therapy?
21. Are you using any digital tools to treat patients?
22. If yes, what tools do you use?

A.2. Evaluation Interviews

A.2.1. Patient Interview

1. **What is your age interval?**
   - 40-50
   - 51-60
   - 61-70
   - 70+
2. **How long have you had your disease?**
   - 0-2 years
   - 3-5 years
   - 6-9 years
   - 10+ years
3. **I am technologically proficient.**
   - Strongly disagree
   - Disagree
   - Neutral
   - Agree
   - Strongly Agree
4. **What are your current challenges with your treatment?**
5. **How much time do you spend on your assigned homeworks?**
6. **How often did you do your daily home exercises before this system?**
   - Never
   - 1-2 days a week
   - 3-5 days a week
   - Every day
7. **How often did you do your daily home exercises with this system?**

- Never
- 1-2 days a week
- 3-5 days a week
- Every day

8. **This system increased my motivation to do the exercises at home.**
   - Strongly disagree
   - Disagree
   - Neutral
   - Agree
   - Strongly Agree
9. **This system helped to improve my health condition.**
   - Strongly disagree
   - Disagree
   - Neutral
   - Agree
   - Strongly Agree
10. **I would like to use this system for my treatment.**
    - Strongly disagree
    - Disagree
    - Neutral
    - Agree
    - Strongly Agree
11. **What did you like about this system?**
12. **Have you had any challenges using this system?**
13. **What should this system improve?**
14. **How should the system be used to give you the most benefit?**

A.2.2. Physiotherapist Interview

1. **What is your age interval?**
   - 18-39
   - 40-50

- 51-60
- 61-70
- 70+

2. **How long have you been working as a physiotherapist?**
   - 0-2 years
   - 3-5 years
   - 6-9 years
   - 10+ years
3. **I am technologically proficient.**
   - Strongly disagree
   - Disagree
   - Neutral
   - Agree
   - Strongly Agree
4. **What are your current challenges in treating COPD patients?**
5. **What challenges have you had in using this system?**
6. **This system increased the efficiency of the treatment.**
   - Strongly disagree
   - Disagree
   - Neutral
   - Agree
   - Strongly Agree
7. **I would like to use this system for the treatment process.**
   - Strongly disagree
   - Disagree
   - Neutral
   - Agree
   - Strongly Agree
8. **What are the added values (advantages) of this system over the current treatment?**
9. **What did you like about this system?**

10. **Have you had any challenges using this system?**
11. **What should this system improve?**
12. **How should the system be used to give you the most benefit?**

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