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A new home-based upper- and lower-limb telerehabilitation platform with experimental validation

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Abstract

The world is witnessing interesting challenges in several fields, including medicine. Solutions to many of these challenges are being developed in the field of artificial intelligence. As a result, artificial intelligence techniques can be used in telerehabilitation to facilitate the work of doctors and to find methods that can be used to better treat methods that can be used to better treat patients. Motion rehabilitation is an essential procedure for elderly people and patients undergoing physiotherapy after physical procedures such as surgery for the anterior cruciate ligament (ACL), a frozen shoulder, etc. To regain normal motion, the patient must participate in rehabilitation sessions. Furthermore, telerehabilitation has become a significant trend in research studies because of the COVID-19 pandemic, which is continuing to affect the world through the delta and the omicron variants, and other epidemics. In addition, because of other special issues like the vastness of the desert area in Algeria and the lack of facilities, it is ideal to avoid requiring patients to travel for all of their rehabilitation sessions; patients should be able to perform their rehabilitation exercises at home. Thus, telerehabilitation could lead to promising developments in this field. Therefore, our project's goal is to develop a website for telerehabilitation that can be used to facilitate rehabilitation

from a distance. We also want to track the progress of patients' range of motion (ROM) in real-time using artificial intelligence techniques, by controlling the angles of the motion of a limbs about a joint.

Keywords: E-Health, public health, deep learning, neural network, telerehabilitation, rehabilitation informatics, range of motion, rehabilitation

1 Introduction

Due to remarkable technological developments, telecare and telerehabilitation have become exciting subjects in medicine because they enable patients to interact with their physicians at home. For this reason, several studies on this topic that focused on in different health specialties were performed [1–5]. Frequently, rehabilitation exercises are necessary and crucial for treating many kinds of musculoskeletal conditions and for postoperative recovery [6]. Due to several factors, it is better for patients to perform rehabilitation programs in a home-based setting to avoid certain issues. One of the most critical factors that was taken into consideration before completing this work on 'telerehabilitation' is the mobility difficulties of people with injuries to the lower or even upper extremities. Furthermore, the area of Algeria is an essential factor, as it is approximately two and a half million square kilometres. It is difficult for patients to reach a hospital, especially in desert areas or remote villages, as it is challenging to find a hospital without travelling 300 km or more in the Sahara. There are several problems for people living in these areas. For example, transportation is not always available, and it may be almost non-existent in remote desert areas. Additionally, the high temperatures in the desert may affect the patients, especially the elderly, as it is difficult for them to move around to perform exercises. Furthermore, one of the most important goals of this study realization is to reduce patient costs, such as transportation costs. With telerehabilitation and with equipment available to almost everyone today, most patients can perform rehabilitation exercises efficiently. In addition, due to COVID-19 social distancing is often necessary. Furthermore, as a result of significant overcrowding, patients often have to wait for at least three weeks to get an appointment to begin their rehabilitation sessions. As a result, this work proposes a telerehabilitation concept that will make rehabilitation easier and more comfortable for patients, doctors, and physiotherapists.

In telerehabilitation, physiotherapists generally use a device called a goniometer to measure patient's range of motion. There are many types of goniometers, such as the universal goniometer. This type of goniometer has two forms of the short-arm goniometer; it is used for smaller joints like the wrist, elbow, or ankle joints. In contrast, long-arm goniometers are used for long levers such as the knee and hip joints[7]. The second type of goniometer is the twin axis electrogoniometer. Generally, it is used for research purposes only, not for clinical rehabilitation [8]. The third type of goniometer is the

inclinometer, which is an arm with a pointer that stays vertical under the impact of gravity. The arthrodiagonal goniometer measures the anteroposterior flexion, cervical rotation, and lateral flexion of the cervical spine [9]. Finally, the smartphone-based goniometer has many advantages, such as its availability and the ease with which it can be used to take of measurement. This application uses accelerometers to calculate the joint angles [10]. Among all these types, the classical goniometer is the most commonly used than the others [11]. However, its utilisation is cumbersome and not always exact, because it overlaps with the motion path of the patient. Another method involves wearing sensors to capture the range of motion, but it is often not available for all patients at home because the prices of these sensors are somewhat high compared to the per capita income of Algerian citizens or the citizens of other third-world countries.

In general, according to [12], telerehabilitation devices can be classified into two groups: the first group contains wearable devices like sensors, and the second group contains context-aware systems. These systems generally rely on computer vision techniques to collect inputs from the surrounding context to detect the subject's movements and react in real-time according to these actions.

The rest of this article is structured as follows. Section 2 introduces the state-of-the-art methods and devices that are used in home-based telerehabilitation. Section 3 presents the motivations and challenges of this study and the project's main contributions. It also includes a questionnaire that was given to several citizens to determine the impact of this work on society in terms of many different aspects. Section 4 discusses the proposed system and the technique used to develop the website. Section 5 describes the website DZtelerehab, and discusses how to use this system. Section 6 explains how pose -detection works and presents the pose estimation technique, which is called MediaPipe. Section 7 revolves around a case study, which focuses on an ACL knee reconstruction. This section also includes some exercises that were recommended after the operation. Section 8 presents experimental studies of real patient cases in which the system was used for four months and demonstrates the performance of the proposed system. Section 9 is a discussion of the project; it also contains the opinions of medical staff and patients concerning the system. Section 10 concludes this paper.

2 Related work

In the literature, several methods and techniques have been used for home-based telerehabilitation including games, virtual reality, sensors, and robotic devices. Many of these methods have also been used jointly; for example, sensors and games have been combined. Reinkensmeyer et al. [13] presented a telerehabilitation system for arm and hand therapy following a stroke. The system comprises a web-based library of status tests, therapy games, and progress charts, and it can include different input devices, such as the low-cost

force-feedback joystick, which is able to aid or resist movement. Karime et al. [14] presented a telerehabilitation system called 'Tele-Wobble' that includes a modified version of a wobble board with sensors and actuators, a software training game, and a web-service architecture that permits the control of an individual's training development from a distance. This system aims to supply doctors with key performance measurements recorded throughout the individual's training session. The results showed that the system might be an effective and low-cost home-based rehabilitation system for patients with ankle deficiencies. Molteni et al. [15] developed a HEAD platform telerehabilitation system to restore limb motor functional abilities. This system concentrated on using low-cost sensors, which were connected to a gaming module for cognitive-motor rehabilitation and inserted into the infrastructure connecting the patient at home with therapists at hospitals who supervised the rehabilitation exercises. Octavia et al. [16] designed a mobile game application as an alternative therapy to facilitate hand rehabilitation for stroke patients. They specified the patient needs in the mobile game application by using the interaction design life-cycle model. The results showed that patients could react in many different ways to the mobile game app and that the games made him want to work on his hand skills. Sierra et al. [17] presented the development and implementation of a functional telerehabilitation system that utilised interactive virtual environments and biomedical technologies for patients with limited upper- and lower-limb movement due to cerebral palsy. The proposed system aids in therapeutic intervention using telerehabilitation through video games developed in Scratch[®] that use Kinect as a movement acquisition interface. The authors programmed a video game in an easily configurable programming language; therapists can modify and adjust the challenges for each therapeutic intervention in an interactive, user-friendly way, according to the progress of each patient, and motivate each patient to continue progressing. The results showed that children with cerebral palsy who were having trouble moving their upper or lower limbs improved.

Demers et al. [18] presented video games and a low-cost virtual reality system. This method was integrated into an at-home individualised treatment project. Cramer et al. [19] used games to treat arm and leg motor deficits, and they evaluated the patient's performance without therapist supervision by attaching sensors to natural objects; their system took in daily trials as input and produced automated actionable reports. Montoya et al. [20] had 24 healthy people test a physiologically adapted Force Defense video game to create practical immersive virtual rehabilitation and to perform biocybernetic adaptation for upper-limb rehabilitation. This method aims to help patients exercise at the desired intensity level while reacting to the virtual environment. The method relies on surface-electromyography (sEMG) signals to reveal fatigue stages in real time and to adjust the game interactively. The system was entertaining and beneficial according to the people who tested it. Furthermore, users of the immersive system demonstrated perfect results, unlike users

of the non-immersive system. Cesarini et al. [21] presented a real-time monitoring program to support telerehabilitation sessions for the functional recovery of patients' lower limbs. The proposed program supports patients performing rehabilitation exercises by monitoring limb movements through low-cost wearable sensors and providing the patients with multimodal biofeedback to improve the quality of the actions performed. The system also assists the therapist in defining patient-appropriate exercises and enables the collection of historical data using cloud-based services to monitor the effects of different therapies and for further analysis. Ongvisatepaiboon et al. [22] presented a machine learning method for estimating the arm's angle of rotation using an accelerometer sensor. They utilise only raw readings from the accelerometer sensor. A body-sensor-network-based approach was suggested by Parisi et al. [23]. The system comprises a few wireless inertial nodes that are worn on the body and used to automatically diagnose unified Parkinson's disease (PD). Furthermore, it can be used in telerehabilitation for the monitoring of PD from a distance. Bariga et al. [24] presented a general approach focused on 3D cameras and neural network-based algorithms that detects static postures for control purposes and automatically aids an elderly person in their rehabilitation exercises using an autonomous method; it also detects abnormal behaviour. Yean et al. [25] proposed two fusion algorithms: complementary filter feedback (CFF) and gradient descent using a quaternion-based Kalman filter (KFGD). The objective of these algorithms is to obtain a drift-free 3D orientation estimate for early-stage rehabilitation. The two algorithms have been shown to control the drift well, and they provide precise results compared to the ground truth from XSENS. A relative evaluation shows that CFF strongly corrects the drifting trend, while KFGD outperforms Madgwick (MW) and adjusts well to the reference values from XSENS. KFGD ensures coherent outputs using smartphone sensor data, while MW is sensitive to direction changes. CFF can fix drift by changing the weights that express the amount of trust in the accelerometer and magnetometer data rather than the gyroscope data. Buonocunto et al. [26] suggested a platform to reinforce the functional recovery of limbs through a telerehabilitation program. They made a low-cost, wearable sensor that could process data in real time. It had a simple interface that met doctors' requirements, and it mitigated the problems that many sensors on the market have. Naembadi et al. [27] presented a telerehabilitation program tested in northern Denmark to evaluate the feasibility of using the TR program as a replacement for the self-training program for persons who had been discharged after knee surgery. Valencia et al. [28] suggested an IMU-POF (inertial measurement unit-polymer optical fibre) sensor fusion system that used a knee sleeve to predict knee flexion-extension angles. The system can be used to quickly and easily determine the correct knee placement, and it can be used for online applications (a few adaptations need to be made to utilise the system in online applications) and for exoskeleton and soft-robotics applications. To measure the knee flexion for patients recovering from knee replacement surgery at home, Antunes et al. [29] used two IMU sensors linked

to the lower limb above and below the knee by a dual-patch system. Many researchers used Kinect V1 or V2 sensors by combining different methods. The goal of [30] was to show the main characteristics of KiReS, a Kinect-based telerehabilitation system for Windows that includes specific elements for users and physiotherapists that make it more user-friendly. For example, the users can watch two 3D avatars demonstrate how an exercise should be performed. This feature can help them improve their exercise sessions. In addition, during the rehabilitation session, they can see an informative list that shows the exercises that should be performed during the session. The system allows physiotherapists, on the one hand, to define personalised rehabilitation therapies. This can be done by combining different exercises that combine predefined movements. In addition, physiotherapists can add tests related to specific diseases so that users can assess their physical condition. On the other hand, they can create new exercises by simply performing them in front of the system and recording them. Perez-Medina et al. [31] proposed ePHoRt, which is a web-based platform for controlling rehabilitation exercises in patients after hip replacement surgery. The architecture has a modular structure to support telerehabilitation programs and to permit the system to be adapted for other motor disabilities. Perez-Medina et al. combined two intelligent modules to assess the quality of the movements made by the patient and to obtain information on the pain level of the patient. They captured the movements of patients by using the Kinect device. Another study [32] has shown that the Kinect sensors have practical restrictions, especially when it comes to knee rehabilitation exercises.

Deutsch et al. [33] suggested a remote console (ReCon) telerehabilitation application that incorporates a virtual reality system. The VR system consists of the Rutgers Ankle prototype robot and a local PC that is connected to a remote PC over the Internet. Six patients who had each experienced a stroke engaged in a four-week training schedule. They used the robot to interact with two VR simulations; the doctor was in the room with them for the first three weeks and in another room during the fourth week. Deutsch et al. evaluated the system's technical performance in terms of the bandwidth and message transmission lag. They found that it would be suitable for clinic-to-clinic communication. The patient's rendering did not decrease in the fourth week. Holden et al. [34] presented the results of a clinical study that provided a virtual environment (VE)-based telerehabilitation system to 11 stroke patients. The system permits a doctor to control interactive VE treatment sessions from a distance for a subject who is at home. The subject wears 2–3 Polhemus sensors: the first is worn on the back of the hand, the second is worn on the upper arm, and the third is connected to an instrument on a held object that captures the movement of the upper arm. Kumar et al. [35] created a virtual reality platform based on technology to improve patients' balance. The platform was improved by off-the-shelf sensors like the Nintendo Wii balance board and Kinect, which measure a person's centre of mass.

Park et al. [36] proposed a portable teleassessment system for the remote estimation of elbow impairments in subjects with neurological disorders. They used a controller device and an agent device to control a mannequin arm and the subject's arm sequentially. They measured the elbow flexion angle and torque using the two devices and transmitted them for teleoperation. To assess the spasticity/contracture of the subject's elbow from a distance, the patient moved their elbow voluntarily, and the physiotherapist observed the movement of the mannequin arm and set the active ROM. The doctor could also assess the muscle strength. Park et al. used two different methods of teleoperation to reduce the effect of network latency due to the speed of the tasks. The first method, for lazy movements, used real-time teleoperations; it utilised control architectures based on the causality of the functions, with an execution similar to that of an in-person examination. Teach-and-replay teleoperations were used for functions involving rapid movements. This method supplied the patient with transparent and stable tactile feedback. In general, this system let the doctor check a stroke survivor's elbow range of motion (ROM), active ROM, passive ROM, muscle strength, catch angle, and spasticity, which depends on speed. Cortese et al. [37] suggested a mechatronics master-slave setup for hand telerehabilitation. The device includes a sensorised glove that works as a remote and a powered hand exoskeleton. The suggested architecture has three advantages. The first is that it furnishes the physiotherapist with an intuitive interface for controlling the rehabilitation exercises. Second, the patient can be helped by this robot-aided physical rehabilitation; the exoskeleton can supply efficient therapy outside of the hospital without the physical presence of the physiotherapist. Third, a sensorised object is integrated into the mechatronics setup, which permits the execution of manipulation exercises and the recording of patient developments. Because of the coronavirus situation, Bouteraa et al. [38] presented a remote rehabilitation solution. This solution is portable and easy to use, and it is able to perform wrist movements (flexion-extension movement and ulnar-radial movement). To carry out a convenient and secure rehabilitation operation, Bouteraa et al. integrated a fuzzy logic-based decision-making system into the control architecture to control the pain level. They used biofeedback, current, and position sensors to estimate the pain level.

Researchers now are more interested in using computer vision techniques because they are cheaper than other methods and provide more benefits. Solongontuya et al. [39] proposed a new stretching-side-pose classification system that uses a three-layer long short-term memory (LSTM) network for four rehabilitation treatment exercises: bird dog, cat camel, cobra stretch, and pelvic tilt. It enables patients to rehabilitate themselves at home. They can control their movements by using an ordinary camera to record simple videos.

It is clear that telerehabilitation often relies on equipment other than a computer to measure and monitor a patient's condition. This is evident from the use of Kinect and other sensors by many researchers. Therefore, the costs of telerehabilitation can be high and not affordable for everyone. In general,

games might not be tailored for rehabilitation applications. Robotics devices raise questions about safety when they are utilised in an unsupervised manner in the home. Therefore, it is necessary to study the use of artificial intelligence in rehabilitation medicine, because it makes devices easier to use and decreases costs and the amount of equipment that is required. Fig. 1 summarises the techniques and devices presented in previous studies that are often used in telerehabilitation.

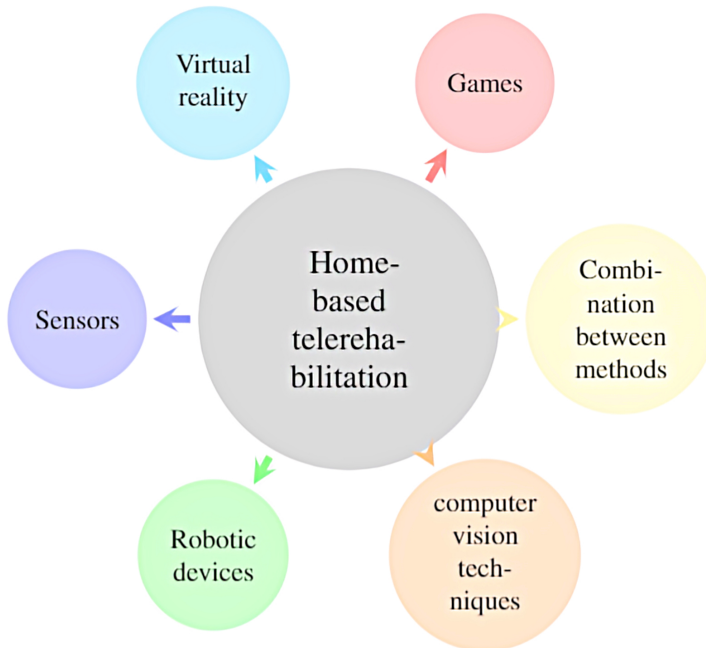


Fig. 1 Methods and devices used in home-based telerehabilitation.

3 Open challenge

As mentioned above, there are many factors that we have taken into consideration as part of the development of our system. The first factor is the problems caused around the world today by the coronavirus and the significant changes that have occurred in daily human life. The second factor is that 80% of Algeria is a desert [40]. The climate in the Algerian Sahara is hot, especially in the summer, and it is not easy to travel through this region. Furthermore, southern Algeria suffers from a lack of hospitals compared to the north, as most hospitals are concentrated in the major cities in the north. In addition, many residents live far away from the nearest hospital; travelling to the hospital exhausts them, and this makes it difficult for them to attend rehabilitation sessions. Another challenge is to reduce the costs as much as possible. For example, in Algeria, the average salary is €213.32, while the price of a Kinect

is about €150. Compared to other devices that are used in telerehabilitation, the Kinect is considered the cheapest. Therefore, it is too difficult for an ordinary worker to acquire or purchase sensors to use in their home. As a result, this project's goal is to reduce the cost of equipment, as well as transportation costs and other expenses. The most important thing is the comfort and safety of the patient.

Therefore, the main contribution of this work is to develop a web platform based on artificial intelligence for telerehabilitation at a low cost; this platform uses only a computer attached to a camera, tablet, or smartphone. The website was tested and provided remarkable results, and it is ideal for telerehabilitation.

Before starting this project, we surveyed about 142 citizens in Algeria. The survey covered a simple random sample. Most of the forms were sent electronically, and others were filled in manually. The most important questions that were included in the questionnaire are the following:

1. **How old are you?:** The average age of citizens in Algeria is an essential factor in our research, especially since the elderly suffer from the most difficulty in mobility. The results are shown in Fig. 2, which displays the range of ages of the respondents.

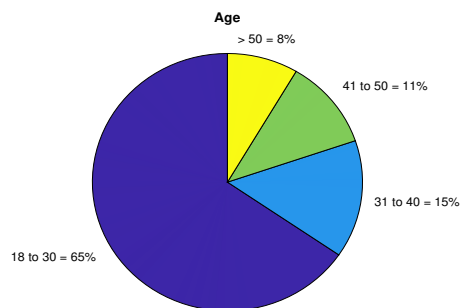


Fig. 2 The age range of the participants in the questionnaire.

2. **Are you living in the city, village, or countryside?:** Fig. 3 represents the geographical distribution of the people who participated in the questionnaire. The largest proportions are concentrated in cities and villages. The conditions in these locations differ, as cities meet most of the requirements for convenient rehabilitation, such as the availability of hospitals and transportation. As for villages, they have fewer resources than cities. Meanwhile, the countryside is different from the cities and villages, and it is more complex.

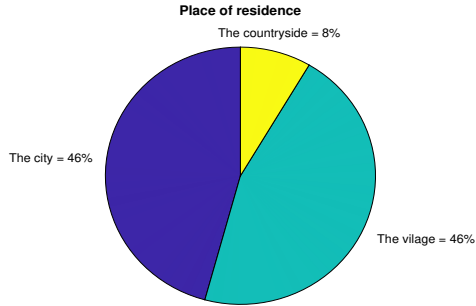


Fig. 3 The place of residence of the participants in the questionnaire.

3. **The factor of distance and proximity to the hospital:** Fig. 4 shows the distances between participants' homes and the nearest rehabilitation centre. This is the primary essential factor that we decided to address and study. In Algeria, transportation is a major obstacle faced by the citizens due to its unavailability, especially in remote areas and municipalities. In major cities, significant overcrowding can cause many dangers to a patient's health when they travel back and forth from the hospital.

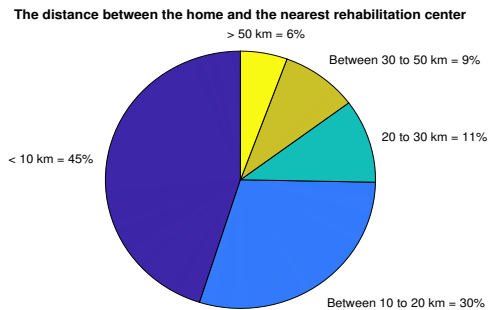


Fig. 4 The distance between the homes of the participants in questionnaire and the nearest rehabilitation center.

4. **The buildings:** Fig. 5 shows the percentage of participants who live in tour buildings. In Algeria, there is a significant amount of social housing, which is also known as social buildings (tours). Social buildings tend to have more than five floors, and they are primarily old buildings that do not have electric elevators; thus, we decided to consider the type of housing (private housing: 66.2%, social buildings: 33.8%) and the floor number to perform a more accurate analysis. If a citizen lives on a higher floor, it will be more

difficult for them to move around, especially if they suffer from a problem in their lower extremities, and the same applies to the elderly.

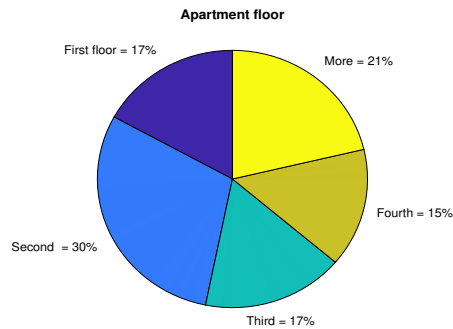


Fig. 5 The positioning of the apartment in the social housing.

5. **The availability of a laptop in the house:** Fig. 6 shows the rates of computer availability among the participants. We also asked the participants the following question: Is there at least a laptop computer or tablet in the house? For our system, the patient only needs a computer or tablet that is attached to a camera and connected to the Internet. Among the participants, 80.4% answered yes to this question and 19.6% answered no. To make things easier for patients, our proposed website and application can work with just a phone.

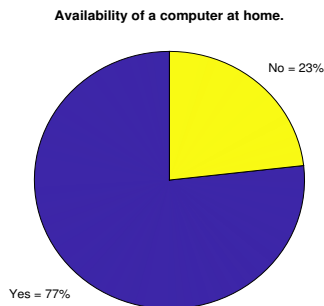


Fig. 6 Availability of a laptop at home.

6. **the mastery of the use of computers:** Then, we asked the participants if they had mastered the use of computers (86.6% said yes, and 13.4% said no), and we also asked this question of **elderly persons** (Fig. 7 which

represents computer proficiency for the elderly). We also considered **the availability of the Internet at home** : 84.1% of the participants have Internet access.

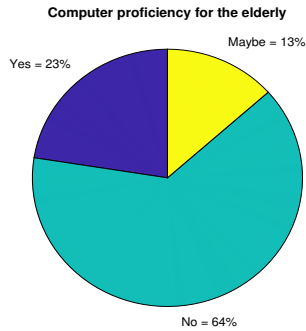


Fig. 7 Computer proficiency for the elderly.

The questionnaire results emphasise the importance of creating a website that helps citizens and patients to avoid costs and obstacles. Moreover, it is advisable to continue to advance the field of telehealth in the future because of its many advantages in the medical field.

4 Proposed system

This article presents a website that can be used to facilitate the rehabilitation procedure from a distance and make it easy and comfortable for the patient and the doctor. The website is based on an artificial intelligence technique that detects the angles and positions of the human body in real time. It is essential to mention that the advantage of using this application is that we just need a web camera connected to a computing device or tablet or even just a phone call to perform human motion analysis. In addition, the other benefit of this computer vision application is that the physiotherapist can view and evaluate the range of motion in real time. Then, he/she can save the data from each exercise and compare these data with the following results. Thus, it is easy to show the patient's progress, obtain rehabilitation results, and digitise data. As a result, the system avoids archiving the data in paper form because physical copies can be damaged, and they require ample storage space. In this human pose estimation system, we have used deep learning, a branch of machine learning. To compute the desired output, a deep learning model learns the hierarchical information in the data and then weights these hierarchies. Generally, deep learning methods have been used in different areas and applications in health informatics [41]. Fig. 8 represents the architecture of the proposed system DZtelerehab.

In this project, the programming languages used are Python and Node.js. For the real-time evaluation, two additional modules are created. The first module is meant to analyse data using a RESTful API (representational state transfer application programming interface). The second module is for the acquisition of movement data using a client application. These modules can connect using the JSON data format to analyse the patient's movements and obtain results. A computer camera is used to capture the movements of the patient. We used Bootstrap 4.1.3 and JQuery 1.11.4 to construct the web interface. The operating system is Ubuntu, and the reverse proxy is Nginx 1.10.3.

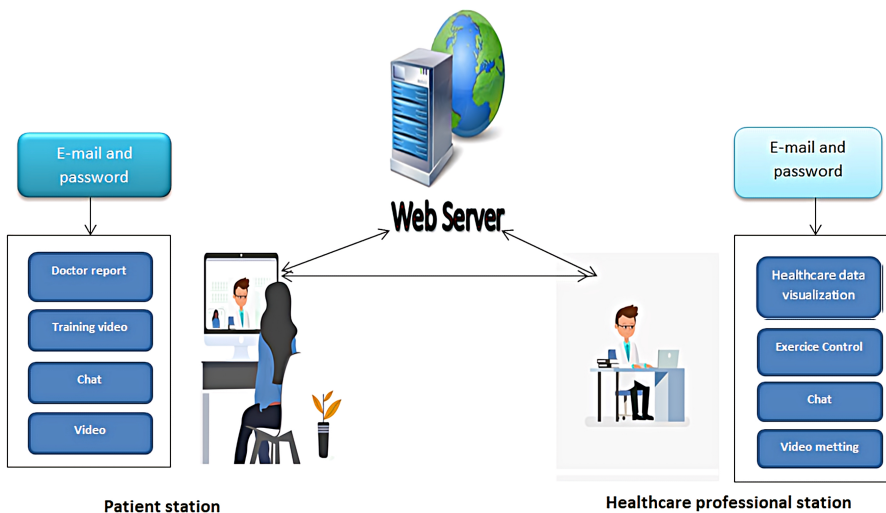


Fig. 8 Architecture of the proposed system.

5 Description of the system DZtelerehab

The website DZtelerehab https://dztelerehab.nbwebp.com/en_US includes three significant actors: the administrator, the doctor, and the patient. The role of the administrator is to organise the working processes, and he/she is responsible for the registration of each doctor and patient; identification and passwords are used to ensure the privacy and security of patient data and information (as shown in Fig. 9, which displays the registration portal for patient accounts). No person other than the administrator can access the patient's portal.

patient / New

Save Discard

Name

Email

Password

Date of Birth

Phone

National ID

Mobile

blood_group

Email

job

gender

Fig. 9 Registration for patient account.

Additionally, the administrator organises meetings between the doctors and patients (as shown in Fig. 10, which demonstrates how to organise a meeting).

ACL knee rehabilitation session

Date

Duration

Participant

Share Link

External Participant

Email **Send Invitation** **Invitation Sent**

Fig. 10 Meeting portal creating.

The doctor can organise the rehabilitation sessions (date and time, exercises, etc.) and then ask the administrator to set up the appointments. Communication between doctors and patients is done using the Internet. The physiotherapist can also send video examples, websites, or any tutorial procedure to facilitate the rehabilitation session and guide the patient. He/she can show the range of motion during the exercise (see Fig. 13), all in real time. Moreover, the doctor can record the session, give feedback to the patient, instruct the patient, write a report about the session, etc. The physiotherapist can save the recording data in many formats (XLS, CSV, PDF, JPEG, or PNG). The patient can access these data, see reports and instructions from the doctor, send messages to the physiotherapist to ask for advice or recommendations, etc. In addition to its simplicity, the system also contains a guide or user manual to help patients to use it. As part of the telerehabilitation assessment,

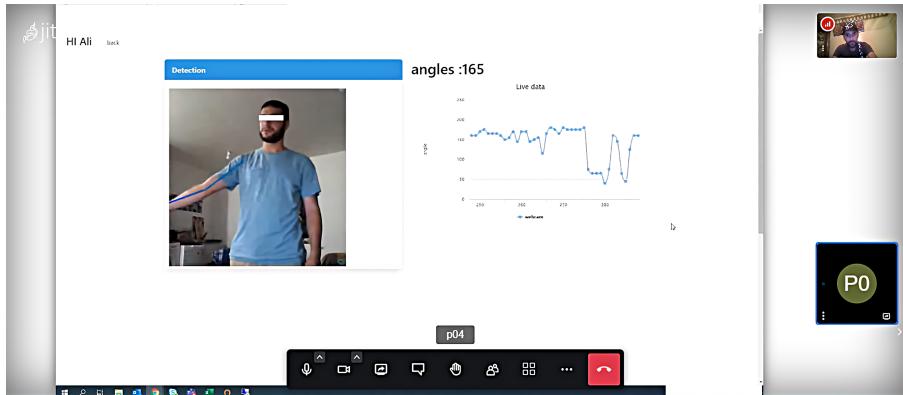


Fig. 11 Physiotherapist view during the session.

the doctor interviews the patient, performs a physical examination, and usually interacts with the patient face-to-face (observations, movement examinations, and standardised tests).

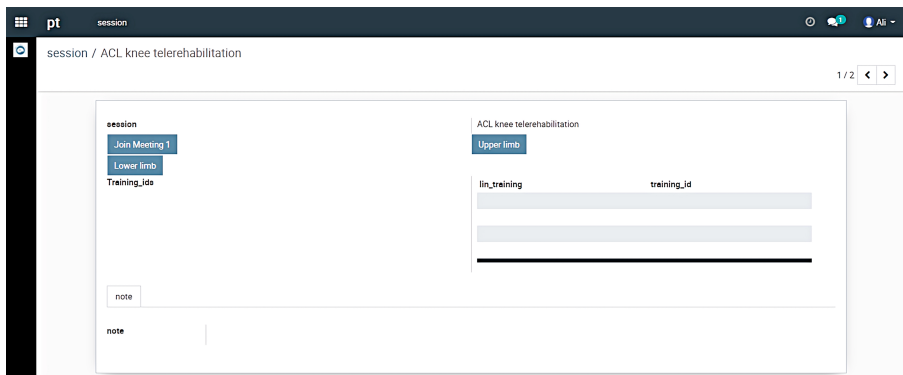


Fig. 12 Patient station view

First, the patient and the doctor must attend the meeting to begin the rehabilitation session. The patient must be in front of the camera. The first step of telerehabilitation is starting and loading the pose module. Second, the doctor sends the patient a video example of the exercise to be performed, or the doctor can explain to the patient how to do the exercise. Then, the patient begins to practice the exercise as shown in the video or as explained by the doctor. At this stage, the physiotherapist tells the patient how many times the exercise should be repeated. The doctor can view the patient in real time and, on the same page, see the values of the angles in the video and a graphic representation of them; the doctor can then compare these data with previous sessions or with the data of a healthy human being. Finally, the doctor can save the session's data and compare it with the data from subsequent sessions

to evaluate the development of the situation. With the platform, we can detect the range of motion of both the upper and lower limbs. Because of this, there are many different rehab exercises that can be performed, such as ACL knee reconstruction or frozen shoulder rehab exercises. The flowchart illustrated in Fig. 13 summarises the system.

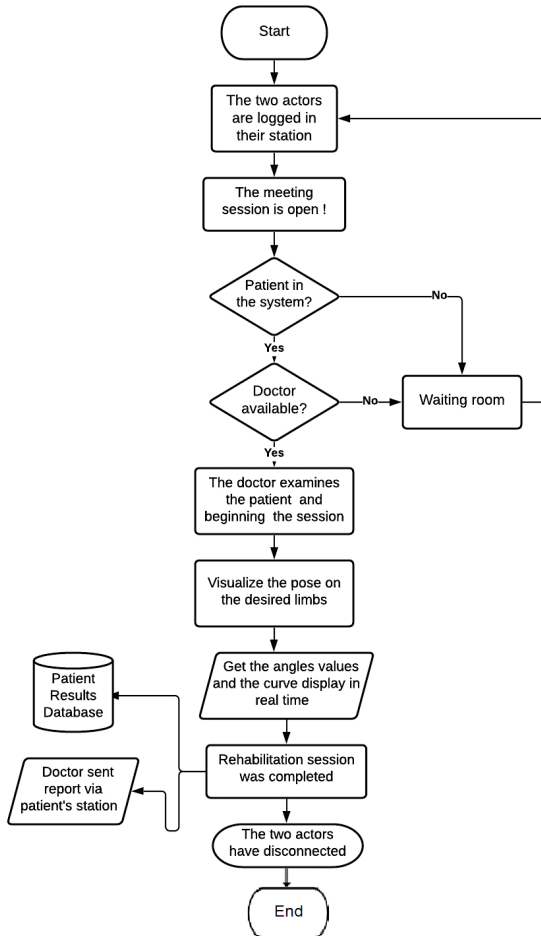


Fig. 13 Proposed system process.

6 Mediapipe human pose detection methodology

The architecture of the provided solution is presented as follows. The input to the system is exported from the camera of the computer. The steps to process

the input classes fall into three stages:

- Detect limbs using a neural network via MediaPipe.
- Calculate the joint angle.
- Show the values of the angles on the screen and draw the curve.

To measure the range of motion, we have used an automated approach called MediaPipe, which is a framework developed by Google for cross-platform ML applications [42]. MediaPipe can perform pose estimation (estimating all the joints and components of the body), so this proposed method can extract the joint coordinates. As a result, it can calculate the angles between a person's joints. For example, inference models built using TensorFlow and TFLite, as well as multimedia processing functions, can be constructed using the MediaPipe framework. We found that human pose estimation from videos plays an essential role in different applications, especially in rehabilitation exercises and the real-time calculation of the range of motion. MediaPipe infers 33 3D landmarks on the human body from RGB video frames by using BlazePose. The MediaPipe library output contains the coordinates of the user's principal basis in the image.

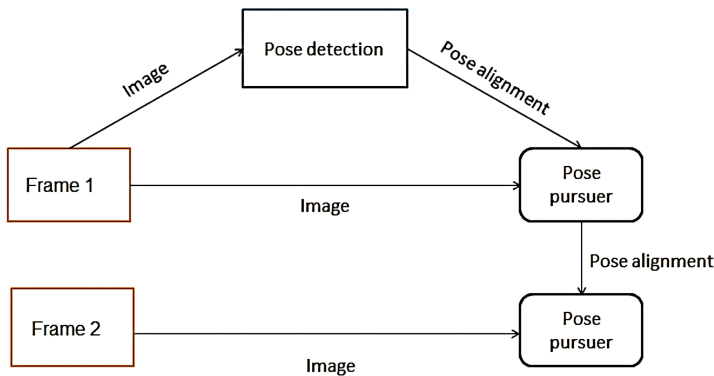


Fig. 14 Human pose estimation pipeline scheme.

A function is programmed to obtain these coordinates. Then, the angles at each human body joint are calculated. The angle between two lines can be easily calculated by utilising analytic geometry. For example, say we have three points (see Fig. 15) $A(x_1, y_1)$, $B(x_2, y_2)$, and $C(x_3, y_3)$. We suppose that AB and BC are skeletal structures, or two bones. The point B is the intersection of the lines AB and BC . The angle between AB and BC can be calculated as follows: Slope of AB is

$$s_1 = (y_2 - y_1)/(x_2 - x_1) \quad (1)$$

BC slope is

$$s_2 = (y_3 - y_2)/(x_3 - x_2) \quad (2)$$

Which s_1 is the slope between the line joining the point A and B , s_2 is the slope between the line joining B and C .

Now, we can calculate the angle between AB and BC :

$$\tan\theta = (s_1 - s_2)/(1 + s_1.s_2) \quad (3)$$

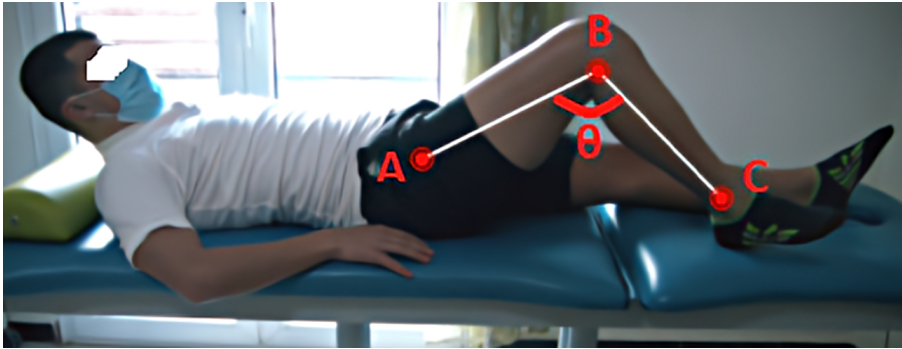


Fig. 15 Joint angle calculation.

7 Case study: ACL knee reconstruction rehabilitation

We began our experimental test with the rehabilitation exercises that the patient must do after an ACL knee reconstruction. The anterior cruciate ligament (ACL) is one of the four main ligaments connecting the femur to the tibia. The ACL stabilises the knee as it moves; a torn ACL can occur if the knee joint over-rotates or if a person receives a direct blow to the front of their knee. If the ACL tears, ultimately, a doctor may suggest surgery to repair it. Before the procedure, the patient will receive either spinal anaesthesia, which will numb their body from the chest down, or general anaesthesia, which will put the patient to sleep for the duration of the surgery. During this arthroscopic procedure, the surgeon makes a few incisions around the knee through which he inserts surgical instruments containing a camera. This camera transmits an image to a television monitor, which the surgeon will look at during the operation. First, the surgeon will remove the residual portions of the torn ACL of the knee. Then, he/she will use part of the patellar tendon as a graft or obtain donor tissue. Then, the surgeon will create attachment points for the graft by digging a small tunnel at the end of the tibia and another at the end of the femur. Next, the surgeon will place one end of the patellar tendon graft in the tibial tunnel and feed the graft up through the knee joint and into the femoral tunnel to make a new ACL tendon. Lastly, the doctor will place small screws in the tunnels at either end of the new ACL to hold it in place. Over

the next six to eight weeks, bone growth will fill in these tunnels, stabilising the graft. The doctor will remove the instruments and close the incisions [43]. Supervised physical therapy has to start two or three days after the operation. In the initial stage of therapy, which lasts around three to four weeks, physical therapy assists the patient in recovering from, essentially, the trauma of having surgery. The loss of the range of motion is another significant side effect of the surgery. The patient will not be able to curve and extend their knee completely, so the patient must do various exercises to improve knee motion. One of these exercises is depicted in Fig. 17, which shows two movements called heel slides and quad sets. The first movement used to improve the range of motion in the knee. The second movement aid rebuild the front thigh muscles. This exercise is meant to improve the knee's passive and active assisted range of motion. The patient needs heel slides to improve the flexion of the knee and quad sets to improve knee extension. After weeks of rehabilitation, the single-leg balance exercise should be performed. The patient needs to improve his balance by standing on one leg. The patient needs to hold on to something at first, but then they should try and progress to standing on one leg without assistance. There are other recommended exercises, such as the inner range quad and static quad exercises.



Fig. 17 A. Heel slides: to lie on the back with legs straight, then to bend the knee and slide the heel up toward the buttocks. B. Quad sets: to try to engage the quad muscles while lying on the back with the leg straight.

8 Data comparison

Generally, the physiotherapist can evaluate the patient by using a goniometer or sensors, so that he/she can consider the patient's progress and write a report. In this project, the proposed method is an artificial intelligence technique that can be used to measure the range of motion. Using this method, we can see that a healthy human being can reach a flexion of 20° (see the 'Healthy' graph in Fig. 18). However, the patient cannot reach the specified range of motion, so we notice a significant difference between the patient and a healthy human being. In the example of ACL reconstruction rehabilitation, the patient often finds it difficult to flex their knee. Thus, he/she does this little by little in order to achieve the desired results. With the proposed

project, we can remotely assist the patient from the start of the rehabilitation session to the end and compare the results of each session with the previous results. Through these curves, it is possible to analyse the effectiveness of rehabilitation.

Experiments were performed on two patients, a 24-year-old patient and a 28-year-old man with a height of 175 cm and a weight of 68 kg. The first patient sustained an injury five years ago while playing football. An MRI of the right knee showed the following results:

- Subtotal rupture of the anterior cruciate ligament;
- Grade 3 lesion of the posterior horn of the internal meniscus;
- Grade 3B lesion of the posterior horn of the external meniscus.

He underwent surgery on October 5, 2021. At the first rehabilitation session, on October 10, 2021, the patient reached a flexion angle of 120°. He found it difficult due to the pain he experienced during the exercises, and the process proceeded very slowly. After ten days, the patient reached 100°, with a slight improvement in the speed of the exercise. Then, on November 16, the patient reached 86° (record 3). That week, there was some swelling in the knee, followed by pain. After nine weeks, the patient reached 67° (record 4), and there was an improvement in the speed of flexion and extension. The patient did not improve for more than a month and a half because he stopped doing the rehabilitation exercises during this period. The following week, there was a slight improvement, and the curve of record 6 indicates this.

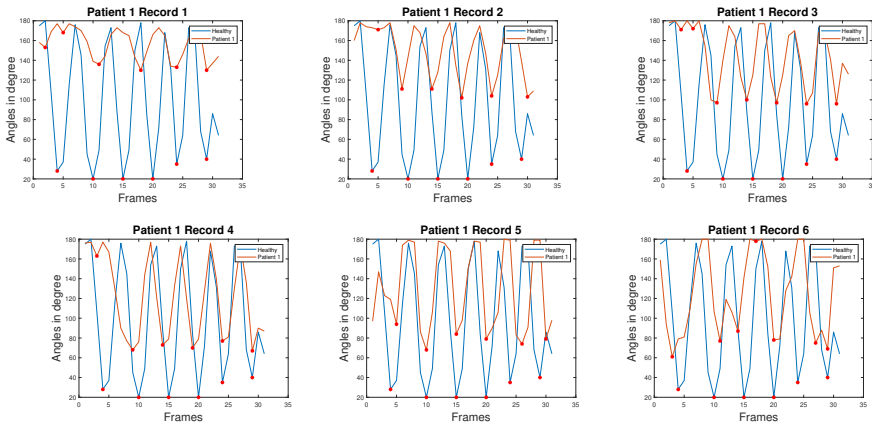


Fig. 18 RoM of knee flexion extension of patient 1.

The second patient was admitted for the surgical management of the anterointernal laxity of the right knee. The surgeon decided to perform a KJ-type ligamentoplasty on the right knee. The surgery was performed on September 26, 2021.

The graphs show the rehabilitation results of heel slides and quad set exercises for the 28-year-old patient. He began rehabilitation sessions on September 30, 2021, with a simple exercise. Through these curves, it is possible to analyse the effectiveness of rehabilitation, make observations, and draw conclusions. The curve of patient 2 (record 1) represents the results from the first week after the operation. As the patient can only reach a flexion angle of 125°, the extension and flexion of the knee were challenging for the patient, and progress was very slow. The graph of record 2 represents a recording of the angles after ten days; there is a remarkable improvement during this period, and the patient was able to reach 98°. He gained 27°. However, the speed of flexion and extension remained small, with some pain. The patient experienced a noticeable improvement during this period, as he was able to reach 62° (see Fig. 19, record 4 of patient 2). Within a week, the patient was moving at a normal speed, slightly improving the flexion. On December 20 (record 5), the patient could reach 47°. Then, on January 3, 2022 (record 6), the patient could reach a flexion angle of 40°.

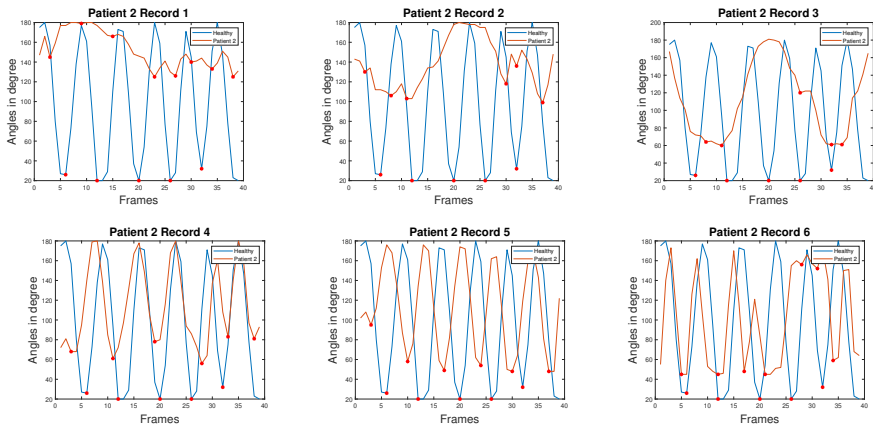


Fig. 19 RoM of knee flexion extension of patient 2.

To compare the performances of the trained models, we must quantify the error between the fundamental values and the predicted values; we compute the root mean square error (RMSE) using the unstandardised prediction data (see Fig.20, which illustrates the differences between a healthy subject and the progression of the patients over four months).

$$RMSE = \sqrt{\frac{1}{R} \sum_{i=1}^R (t_i - y_i)^2} \quad (4)$$

where t_i is the mean of the minima (per training session) of the angles of flexion of the patient, y_i represents the flexion angle of a healthy person, and

R is the number of training . Table 1 illustrates the flexion progression of the patients over six records.

Table 1 Optimal patients flexion progression during six records.

Optimal flexion	Patient 1	Patient 2
$R1$	130.00°	125.49°
$R2$	102.32°	98.00°
$R3$	95.86°	59.00°
$R4$	66.60°	56.10°
$R5$	67.83°	46.62°
$R6$	60.83°	40.00°

R: record.

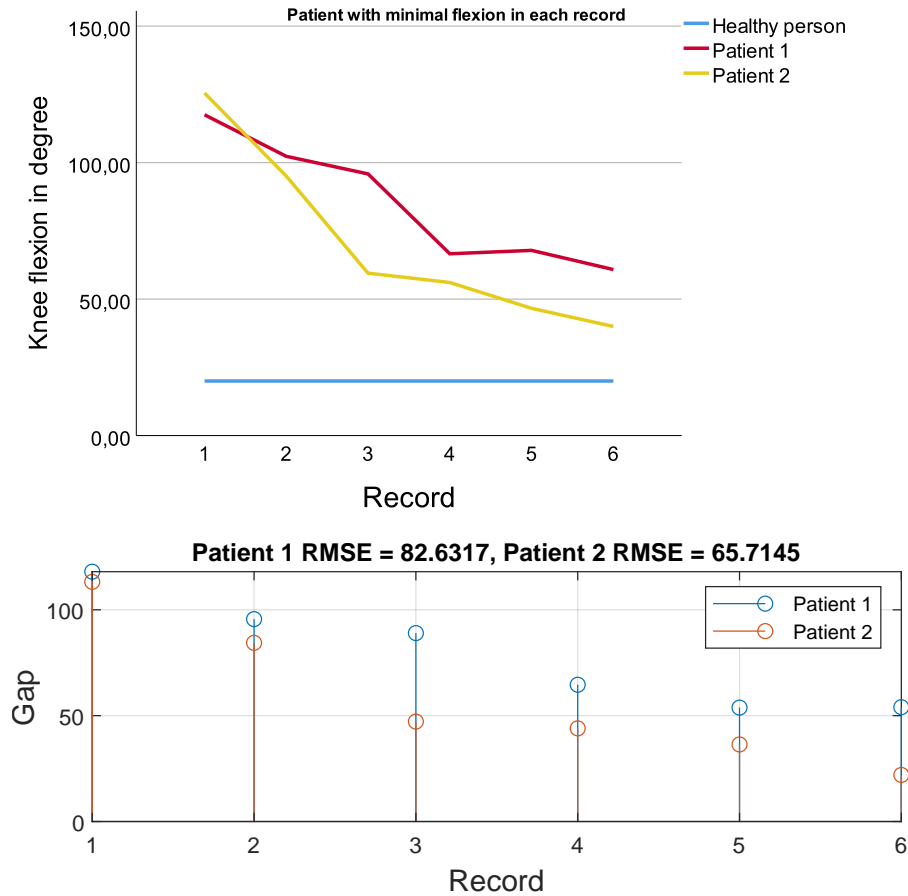


Fig. 20 Flexion differences between a healthy subject with the progression of the patients through 4 months.

Through the examination of and follow-up with the two patients, we noticed that the second patient improved more quickly than the first because the second patient was attending rehabilitation sessions. If the patient stops the rehabilitation process, he may lose what progress he has gained, and the process of flexion and extension becomes somewhat tiring. The second patient reached a flexion angle of 40° in four months, while the first reached a flexion angle of only 60° . To help the patient to recover quickly, the physical therapist tells the patient to perform the exercises as consistently as possible, even at home.

9 Discussion

Rehabilitation often lasts for more than ten weeks, so in this research, we proposed a method that allows doctors to inspect and monitor the patient from a distance. Because of remote rehabilitation, during this long period, the patient will not have to face several obstacles. For instance, travel hardships, burdens, and costs will be reduced. Through this work, we have many advantages that comfort the patient and allow them to avoid many stressful, arduous, and costly factors. Moreover, our system plays a significant role in facilitating the doctor's work. Furthermore, compared with the other solutions like Microsoft Kinect or any other sensor, this method is more economical and easier to use. Additionally, if sensors are misplaced, a good detection may not be obtained, and if these sensors are attached to the body for a long time, the patient may be uncomfortable.

The most crucial point is protecting patient data because medical information is sensitive and medical privacy is important. This type of application could allow more motivational and safer home workout practices, and it also increases accessibility.

Nevertheless, some challenges must be considered, and solutions to them must be found. The first limitation is the lack of familiarity with technology of some older people, and the difficulties they will encounter when they use the system, especially if they are alone, require further intervention. This is why the patient's page has been simplified as much as possible on the website. Additionally, some people will not participate in remote rehabilitation; they always prefer to see a doctor face-to-face. These people believe that rehabilitation sessions are better when a physiotherapist is there in person compared to when they are done over the phone.

Another limitation is the instability of the patient's Internet connection. Sometimes, there is a bad connection, so it is hard to carry out a telerehabilitation session effectively. As a result, we proposed a second solution: the exercise session can be recorded and sent to the physiotherapist, who can evaluate the patient's progress later on.

Finally, we conducted a survey about the project and the extent of its impact on patients (first) and medical staff (second). The opinions and comments were as follows:

- Doctor: The system is good regarding the reliability of angle measurement. It also serves to help patients to do the rehabilitation sessions at a distance. I see the project as very important and opens up other horizons in the field of rehabilitation, mainly since it uses affordable equipment available in almost every home. I think the project deserves to be developed more, and why not include other medical fields through which the doctor can intervene remotely.
- Physiotherapist: We already recommend many exercises at home. Monitoring a patient's condition remotely is excellent! Also, in the clinics, we suffer from many cases, so it is difficult for us to monitor them all simultaneously. Thanks to the website and the data, we can do the work in less time than at the clinic. The problem of Internet cuts sometimes remains an obstacle for us. Nevertheless, work, in general, is beneficial.
- First patient: I do not understand much in the field of informatics, but using the site is effortless. Also, when I understood the development of my condition through the graphs, it stimulated me a lot and made me feel that my condition was improving significantly.
- Second patient: I prefer this method because it is inexpensive and keeps me from traveling to the centre. I could not find an appointment in the hospital soon, and this made me go to the private centres, which are more expensive. I hope that the idea of using modern medical technologies will spread as well, especially in Algeria where it is almost rare.

10 Conclusion

Telerehabilitation is currently becoming tremendously important, and it is experiencing unprecedented demand and development. This is due to its effectiveness and the services it provides, especially to patients. In critical situations, such as the coronavirus pandemic, that oblige us to stay at home to avoid infection and limit the spread of the virus, telerehabilitation can be incredibly helpful. In addition, an essential factor is the difficulty some patients face in moving from place to place, particularly when a patient has lower-limb injuries; it is recommended that these patients perform rehabilitation exercises at home. The same applies to the elderly. With the growth of digital technology and its use in many fields, such as medicine, it is now possible to do research and find real-world solutions to many such problems.

In today's world, we need to come up with different methods to minimise costs and provide more efficient access to services. Telecare improves the care that patients receive, provides better patient outcomes, and lowers costs.

Declarations

Ethics approval and consent to participate. No indication of ethics is given.

Consent for publication. Permission has been taken from all patients and participants in this research project to share their data or photographs.

Availability of data and materials. The data that support the findings of this study are available upon request from the authors.

Competing interests. The authors have no competing interests to declare that are relevant to the content of this article.

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Authors' contributions. **AL, RK,** and **AC:** conceptualization and formal analysis. **AL, RK, AC,** and **AK:** methodology and data curation. **AL, RK,** and **AC:** software and visualization. **RK, AC,** and **AK:** validation. **RK** and **AC:** investigation. **RK, AC,** and **AK:** resources. **AL, RK,** and **AC:** writing—original draft preparation and project administration. **AL, RK, AC,** and **AK:** writing—review and editing. **RK, AC,** and **AK:** supervision. All authors have read and agreed to the published version of the manuscript.

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