Koc. J. Sci. Eng., 5(1): (2022) 54-62 https://doi.org/10.34088/kojose.1024433

Kocaeli University

Kocaeli Journal of Science and Engineering

http://dergipark.org.tr/kojose

Cyber-Physical System based E-Health: Knee Joint Physical Therapy Monitoring

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Article Info

Research paper

Received : *November 16, 2021*
Accepted : *December 14, 2021*

Keywords

Cyber Physical System
E-Health
Knee Joint Angle
Osteoarthritis
Physical Therapy

Abstract

A cyber-physical system (CPS) uses sensors/actuators to associate the physical world with a system capable of computing. CPSs include software systems, communication technologies, and sensors/actuators, including intelligent embedded system technologies to interact with the real world. It is possible to monitor and control all physical processes without human factors by connecting the mechanical systems equipped with information technologies and establishing communication among themselves. In this study, a CPS system that offers a cost-effective and easy-to-apply physical therapy opportunity is proposed for post-hospital home follow-up of knee osteoarthritis, which can be seen in many people over a certain age. The proposed system consists of a hardware module consisting of two potentiometers, a microcontroller and a WiFi module, and a software module to monitor the movement of the knee joint point daily and to save the data in the database. Maximum knee flexion angle, exercise duration and success rate measurements were used to measure the progress of physical therapy. The CPS prototype developed for the healthcare field will make significant contributions to reducing the duration of physical therapy and increasing its reliability by eliminating the possibility of wrong/incomplete exercises.

1. Introduction

Cyber-Physical Systems (CPSs) are systems that seamlessly integrate computing components, network communication and physical processes for a specific purpose. CPS has four fundamental components. The first is the physical world, which refers to physical events to be monitored or controlled remotely. The second is the next generation of embedded devices that process information and communicate with the surrounding environments over a communication network. The third is a communication network and sensors/actuators, which is a bridge between cyber systems and the physical world. The last is the software [1]. With the concept of the Internet of Things (IoT), CPS, which started to remove the boundaries between the real and virtual world, is one of the cornerstones of Industry 4.0, one of the important issues of today's technology [2].

CPS, which is a highly complex and computationally intensive system, can be used in many healthcare applications. It offers stronger communication, more computation, and higher security compared to its current alternatives. Rapid advances in wireless communication technologies and wearable sensors used in healthcare make CPS a strong candidate for healthcare applications [3, 4]. In an exemplary CPS for healthcare, Patients who need home care or continue their treatment in the hospital can be monitored remotely and clinicians can offer treatment recommendations. First, patient data, which are collected using various sensors and sent to the cloud storage/remote server via a gateway over the wireless communication medium, is processed. By analyzing the sensor data, an alarm is generated and transmitted it to the observation center. The experts in the observation center can access patient data in real time via the cloud, and if needed, the patient's condition is evaluated according to the responses from other health systems, and the decision taken is sent to the control/activation component. Last, the patient is furnished with medical attention [5]. In this way, diseases

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can be categorized and treatment outcomes can be improved by collecting all data from patients and analyzing treatment methods and results [6, 7].

Osteoarthritis (OA), which is mostly seen in the elderly and affects the musculoskeletal system, causes health problems such as pain, joint stiffness, swelling, and difficulty in daily activities. In our body, this disease mostly affects the knee joints [8]. Medication and physical therapy come to the fore in the traditional treatment of OA patients. Physical therapy should be continued for a certain period at home after treatment. Many studies have shown that the knee can perform its normal physical functions by significantly reducing the pain caused by the disease with physical therapy [9-11]. Therefore, medical professionals should monitor the patient's knee movements in the home environment. Continuous evaluation of the knee joint angle allows immediate intervention in unwanted situations, allowing the treatment to achieve the desired result. Exercise performance in physical therapy can be characterized by monitoring changes in knee flexion/extension.

1.1. Related Works

[12] develops a novel approach, consisting of multiple flex-sensors mounted on a supportive cloth and microelectromechanical systems (MEMS) vibratory gyroscope, for measuring the knee joint angles for the surface electrical stimulator system. For the evaluation of knee angle motion, lower extremity joint angles and segment angles were estimated from data measured by wireless MEMS vibratory gyroscope and flex-sensors. These data were used to see the effectiveness of rehabilitation training, especially for spinal cord injury (SCI) patients.

[13] provides an approach to measure and monitor human body joint angles using inertial measurement unit (IMU) sensors that facilitate the remote assessment of patient activities for therapists and doctors. Euler angles are sent to the computer via Bluetooth to calculate the knee joint angle. In the experiments, it was determined that the IMU measurement system outperforms existing conductive fiber optic sensors and flexible sensors in accurately measuring knee joint angle.

Different joint monitoring methods and sensing technologies are compared in [14]. A discussion on the data processing, interpretation and analysis techniques of the sensors is also presented.

In [15], an accurate, low-cost, flexible wearable sensor has been developed that includes a retractable reel, a string, and a potentiometer to evaluate and monitor joint movements. The sensor estimates the joint angles in correlation with the amount of skin stretch measured by the change in the length of the string. An optoelectronic system was used to evaluate the accuracy of the designed sensor in predicting knee joint angles.

[16] proposes a health monitoring system that can classify lower extremity movements such as assisting, lying and standing, using the angle and acceleration components of the knee joints of the elderly and physically disabled. Two potentiometers attached to a wearable frame and an IMU sensor attached to the thigh region were used to measure knee joint angles and accelerations. The data received from both sensors is transferred to the device via Bluetooth.

[17] proposed a novel sensing technique using e-textiles and triaxial accelerometers to analyze standing human motion. The proposed technique was used to measure the knee flexion-extension angle in different movement tasks (monopodalic flexions and walking at different speeds). The results were compared with a measurement system with an inertial measurement unit (IMU).

[18] evaluates the possibility of predicting 3D lower extremity joint kinematics during hip and knee exercises with data collected from a single inertial measurement unit (IMU). The proposed approach was applied to ten healthy young people. The results obtained were compared with measurements collected via a stereo photogrammetric system.

In [19], low-cost and non-invasive health and activity monitoring systems that the elderly can use at home were examined. A survey was conducted on textile-based sensors. At the same time, the future of remote monitoring systems and compatibility with communication technologies are discussed.

Apart from the studies detailed above, wearable sensors such as inertial measurement units (IMU) [20, 21], ultrasonic sensors [22], rigid electrogonometers [23, 24], flexible sensors [25], and e-textile sensors [26, 27] used to measure knee joint angle are evaluated in terms of power consumption, cost, safety, ease of use and compatibility with the human body.

Most of the studies mentioned above usually involve measuring and monitoring the joint angle. Some of these studies use smartphones and apps to provide an effective knee joint angle measurement system for real-time monitoring of knee angle. In our study, we propose an effective CPS that integrates two potentiometers, a WiFi module, and a Web interface for remote monitoring and analyzing the progress of physical therapy by a therapist/physician. Despite the limitation that potentiometers are not durable due to friction, the results obtained from the wearable sensor with a potentiometer are more reliable than accelerometers and flexible sensors affected by environmental conditions [28]. The proposed system includes measuring the knee joint angle, saving it in the database on the remote server, and showing the daily exercise success rate and exercise duration information on the graph according to the maximum angle value (limit) entered by the doctor from a Web interface. The proposed system provides a very cost-effective and easy-to-apply physical therapy opportunity for the follow-up of the treatment of a health complaint that can be mostly seen in many people over a certain age. It allows the patient to continue the treatment processes without the need for any clinical environment and independent of the assistance of the therapist/physician.

2. The Proposed Model

Figure 1 shows an example scenario of the proposed CPS system. In this scenario, the system has three components. The first is the section where the knee joint angle measurement is calculated while the patient is exercising at home, and the data is sent to the network. The second is the process in which data is processed after reaching the remote server. The third part is the part of informing the experts who will guide the treatment process according to the data obtained after these two procedures. In-home operations form the hardware layer portion of the CPS. In this layer, the data coming from the array is taken by analog sensors and first converted into digital data with ADC, then these data are processed on the microcontroller to obtain angle information. Angle data is sent to the remote server over the internet via the WiFi module. The data coming to the remote server is taken into the database by the Web service. Instant training data recorded in the database is displayed graphically according to weekly, monthly and annual periods. The physician or therapist monitors the patient's treatment process remotely. Finally, they contact the patient via e-mail or telephone via the system to provide information about the treatment.

Figure 2 shows the hardware architecture of the proposed model. The system consists of (a) NodeMCU microcontroller card and ESP8266 WiFi module, (b) Analogue to Digital Converter - ADC, (c) Organic Light Emitting Diode - OLED display and (d) potentiometer.

Figure 1. The proposed CPS for healthcare.

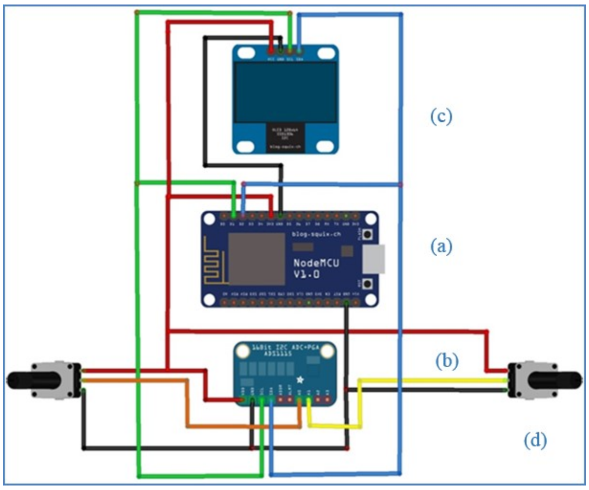

Figure 2. Hardware architecture.

NodeMCU (Node Micro Controller Unit) in Figure 3 is a microcontroller board, which is preferred because it is cheap, capable, and open source. It operates with low voltage. Thanks to the ESP8266 WiFi module, IoT applications can be performed. NodeMCU can work as a Web client or a Web server through HTTP libraries. NodeMCU has an advanced hardware I/O interface that can be adjusted and edited. It also has a simple API.

A typical single-turn potentiometer is often called a pot. It is a mechanically operated rotary analog device, which can be used in a wide variety of electrical and electronic circuits. Potentiometers can be used in two different ways, as a voltage divider and variable resistance. If the potentiometer is used as a voltage divider, the outer terminals are connected to the + V and GND end respectively. The middle terminal indicates the moveable contact called the screw and produces a value between 0 and +V depending on its physical position. In the case of the variable resistor, one of the outer terminals is short-circuited with the middle terminal. The resistance varies from 0 Ω to the maximum resistance of the pot as the screw is moved.

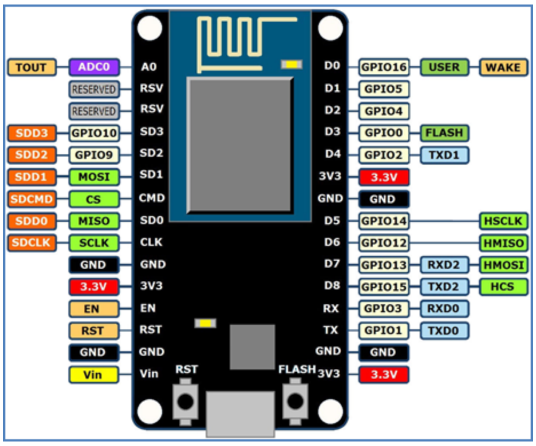

Figure 3. NodeMCU 1.0.

3. Angle Measurement with Potentiometer

Two potentiometers, which are analog circuit elements, are used to find the flexion angle from the knee joint point. Potentiometers are positioned symmetrically on both sides of the knee thanks to the specially designed mechanical parts with the 3D printer. Potentiometers that can rotate between 0-270 degrees in a single turn have a value of 100K. Analog values from potentiometers are converted into digital data with an n-bits ADC so that they can be processed in the microcontroller. As the potentiometer is rotated, the ADC converts this analog resistor value to a value between 0 and $2^n – 1$. These values are used to obtain the angle value of the potentiometer from 0 to 270 degrees. Eq. (1), (2), and (3) are used to make this calculation.

$$\theta_{rigth} = (X - in_{min})\left(\frac{out_{max} - out_{min}}{in_{max} - in_{min}}\right) + out_{min} \quad (1)$$

$$\theta_{left} = (X - in_{min})\left(\frac{out_{max} - out_{min}}{in_{max} - in_{min}}\right) + out_{min} \quad (2)$$

$$\theta_{mean} = (\theta_{rigth} + \theta_{left})/2 \quad (3)$$

where θ_{rigth} is the angle value measured on the right side of the knee, θ_{left} is the angle value measured on the left side of the knee, θ_{mean} is the average of the measured angle values, X is the measured value from the potentiometer, in_{min} is the minimum value measured from ADC, in_{max} is the maximum value measured from ADC. out_{min} shows the minimum angle value of the potentiometer while out_{max} is the maximum angle value of the potentiometer. The measured angle value with the potentiometer resistance value can be shown in Table 1.

Table 1. The measured angle value with the potentiometer resistance value.

Angle value measured from potentiometer (°)	The potentiometer resistance value (K)
5	1.2136296499
10	2.4272592999
15	3.6408889499
30	7.2817778999
45	10.9226668499
60	14.5635557999
90	21.8453336999
120	29.1271115999
135	32.7680005499
150	36.4088894999

4. Experimental Results and Analysis

Since there is one analog input on the NodeMCU microcontroller card used in the study, the values of the two potentiometers were read using a 16-bit four channel ADC. Therefore, the analog input is converted to a numerical value between 1 and 65536. The OLED screen displays the average knee joint angle value, number exercise repetitions, exercise status and IP number. The connection diagram of the designed circuit is shown in Figure 2. Socket cables and insulating tape are used for connections. After the connections were made, a prototype was produced as shown in Figure 4. The developed hardware is mounted on the knee brace and compatible with the knee joint point. Figure 5 shows the prototype wearable on the knee during exercise.

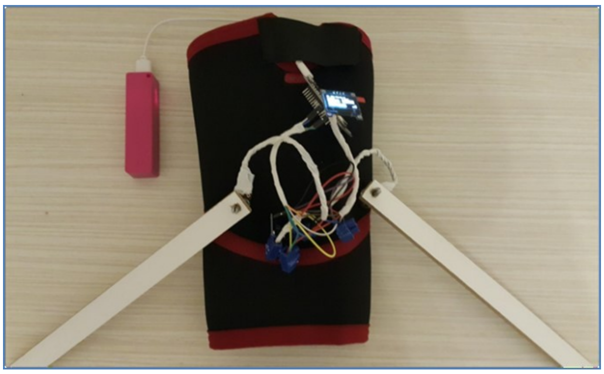

Figure 4. Experimental setup.

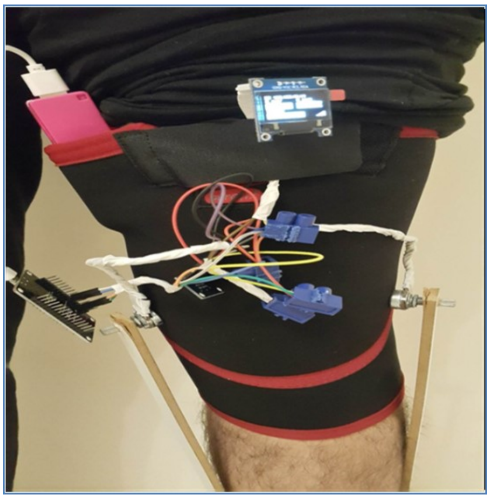

Figure 5. Wearable prototype on the knee.

The CPS software layer is used to receive data from potentiometers, convert these data to angle values in the microcontroller, connect to the internet with WiFi technology and send the data to the server, and save and analyze the data in the database. In our study, patient data are sent over the URL to the Web service on the server side via ESP8266. Using the PHP Web service, the angle, IP and user name information from the patient is retrieved from the URL using the GET method, and each data is stored in the database with the help of SQL commands. Then, the data in the database is analyzed and the treatment information is shown to the doctor / specialist as graphics/text. In addition, this information is sent via e-mail or SMS upon request.

After the Internet connection is established with the ESP8266 module, The patient's ID information, the targeted knee joint angle value and the Web service parameters during the exercise are entered into the interface shown in Figure 6 by the patient, doctor or specialist.

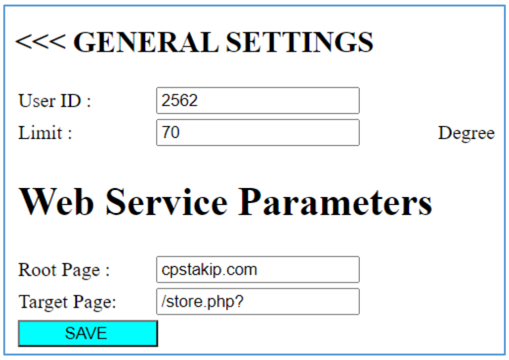

Figure 6. User general setting interface.

The Web interface shown in Figure 7 provides instant monitoring of the exercise over the Web. The physician / specialist can instantly monitor the exercise by connecting to the device via the IP address of the device registered on the Website.

DEGREE VALUES	
RIGHT	LEFT
76.90	79.40
AVERAGE	
78,15	

Figure 7. Exercise tracking screen.

The Web interface where patient information is entered and recorded in the database is shown in Figure 8. An authorized person enters the patient's username and other personal information. This information is recorded in the database. With the password and user name specified in this section, the patient can log into the system via the Website and contact the doctor or authorized person. In addition, the person can view the tracking of past exercise information through the system.

As seen in Figure 9, authorized physicians or specialists can access the information of registered patients through the system. This information can be deleted or updated. The data recorded in the database are shown graphically in order to make it easier for patients and specialists to understand. The date and exercise data of the exercise information are recorded in the database. A single value is recorded in the database by taking the average of the data made during the exercise. Figure 10 shows the graphical representation of patient exercise information, time data on the x-axis, and angle values on the y-axis. The success time indicates to the first time to reach the limit value entered during exercise. Eq. (4) is used to calculate the success rate of the exercise.

$$SuccessRate = \frac{the\ number\ of\ angle\ values\ above\ the\ limit}{total\ number\ of\ angles} \quad (4)$$

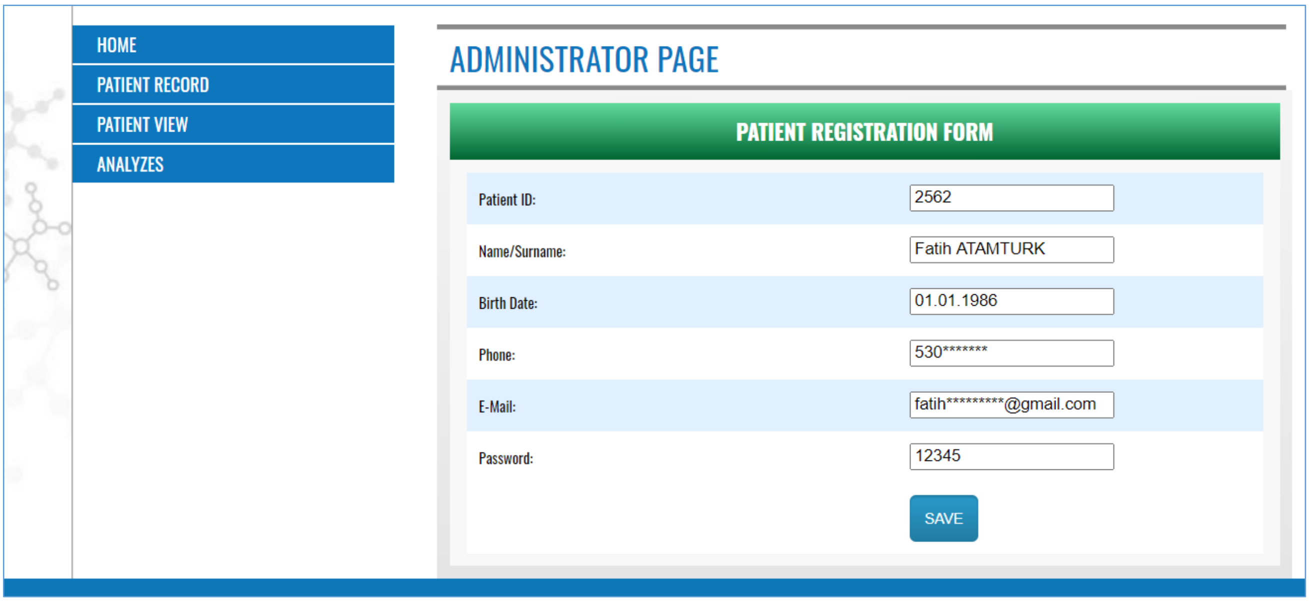

Figure 8. Patient registration form.

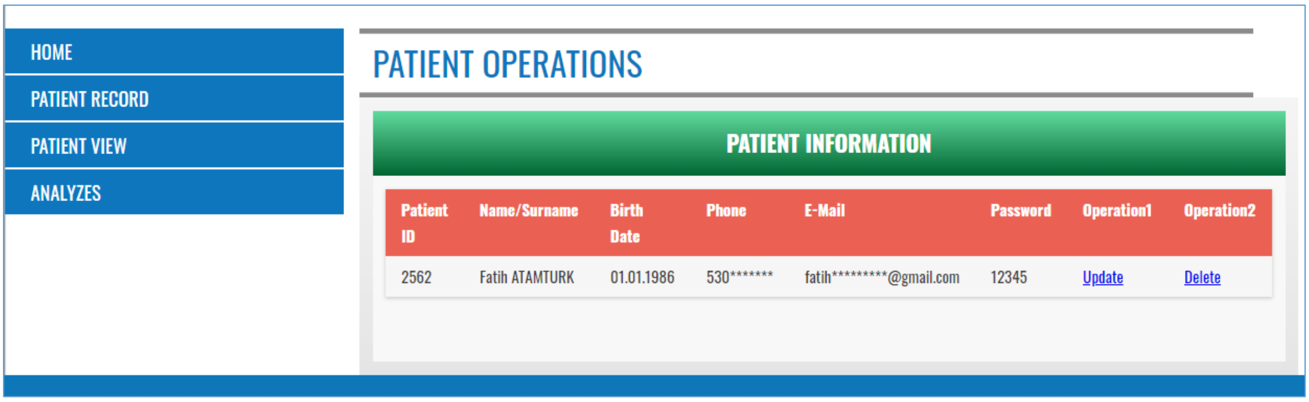

Figure 9. Patient information monitoring.

5. Conclusions

The loss of mobility in the knee joints, which play an indispensable way in the daily life activities of people over a certain age, causes serious social, mental and physical consequences. It is very important to follow the condition of the knee joints in post-treatment physical therapy. In the study, CPS that is an effective and easy to implement, is developed that integrates two potentiometers, a WiFi module, and a Web interface to remotely monitor and analyze the progress of physical therapy by the therapist / physician. As a result, CPS studies in the field of health, which directly affect people's living standards, will save time and costs by ensuring that health services continue uninterruptedly after treatment, especially at home.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

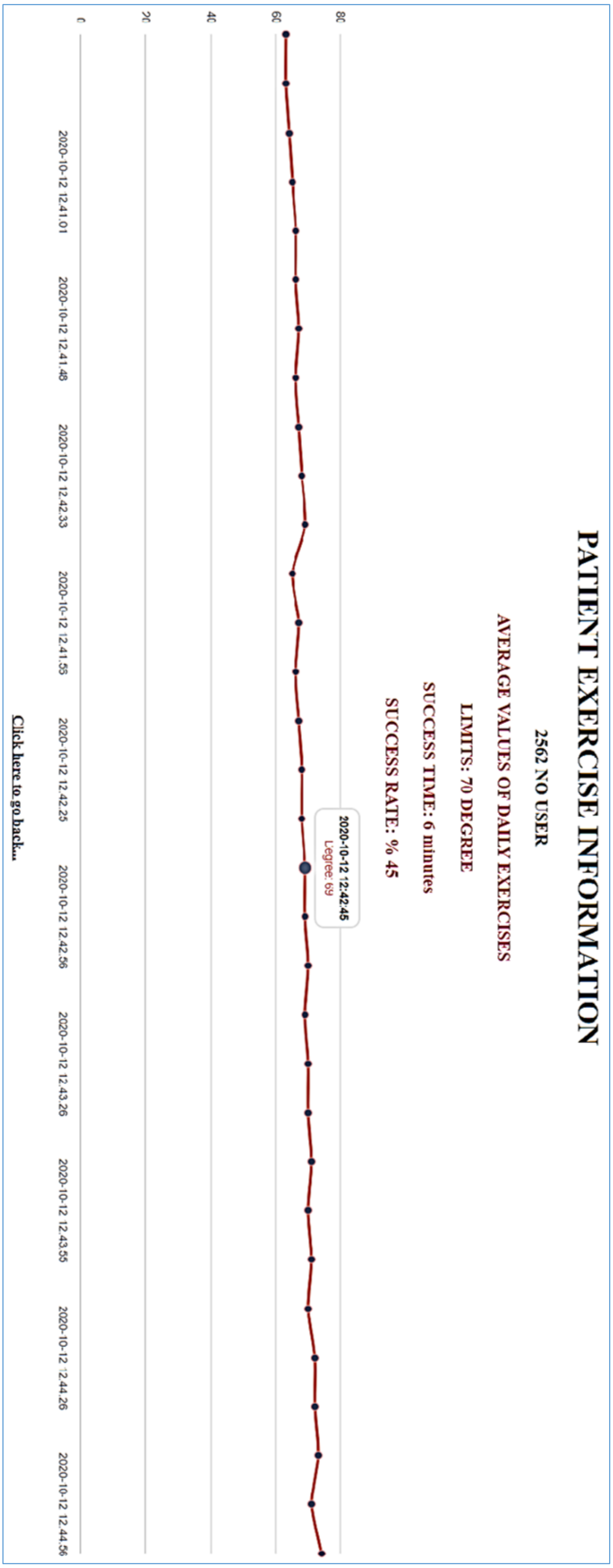

Figure 10. Patient exercise chart.

References

[1] Wang J., Abid H., Lee S., Shu L., Xia, F., 2011. A Secured Healthcare Application Architecture for Cyber-Physical Systems. Control Engineering and Applied Informatics, **13**(3), pp. 101–108.

[2] Jazdi N. 2014. Cyber Physical Systems in the Context of Industry 4.0. Proc. IEEE International Conference on Automation, Quality and Testing, Robotics, Cluj-Napoca, Romania, 22-24 May, pp. 1-4, DOI: 10.1109/AQTR.2014.6857843.

[3] Milenković A., Otto C., Jovanov E., 2006. Wireless Sensor Networks for Personal Health Monitoring: Issues and an Implementation. Computer Communications, **29**(13-14), pp. 2521–533.

[4] Jovanov E., Milenković A., Otto C., Groen P. C. D., 2005. A Wireless Body Area Network of Intelligent Motion Sensors for Computer Assisted Physical Rehabilitation. Journal of NeuroEngineering and Rehabilitation, **2**(1), pp. 1–10.

[5] Shah A. H., Syed M. A., Mustafizur R., 2014. Review of Cyber-Physical System in Healthcare. International Journal of Distributed Sensor Networks, 10, pp. 1–20.

[6] Lounis A., Hadjidj A., Bouabdallah A., Challal Y., 2012. Secure and Scalable Cloud-Based Architecture for E-Health Wireless Sensor Networks. 21st International Conference on Computer Communication Networks, Munich, Germany, 30 July-2 Aug., pp. 1-7, DOI: 10.1109/ICCCN.2012.6289252.

[7] Insup L., Sokolsky O., Chen S., Hatcliff J., et al., 2012. Challenges and Research Directions in Medical Cyber-Physical Systems. Proceedings of the IEEE, **100**(1), pp. 75–90.

[8] Tang L.-A., Yu X., Kim S., Han J., et al., 2012. Multidimensional Sensor Data Analysis in Cyber-Physical System: An Atypical Cube Approach. International Journal of Distributed Sensor Networks, **8**(4), pp. 1550–1329.

[9] Emmerzaal J., De Brabandere A., Vanrompay Y., Vranken J., Storms V., et al., 2020. Towards the Monitoring of Functional Status in a Free-Living Environment for People with Hip or Knee Osteoarthritis: Design and Evaluation of the JOLO Blended Care App. Sensors (Basel), **20**(23), pp. 6967.

[10] Bennell K., Hinman R. S., Wrigley T. V., Creaby M. W., Hodges P., 2011. Exercise and Osteoarthritis: Cause and Effects. Comprehensive Physiology, **1**(4), pp. 1943–2008.

[11] Zampogna B., Papalia R., Papalia G.F., Campi S., Vasta S., Vorini F., Fossati C., Torre G., Denaro V., 2020. The Role of Physical Activity as Conservative Treatment for Hip and Knee Osteoarthritis in Older People: a Systematic Review and Meta-Analysis. J. Clin. Med, **9**(4), pp. 1167.

[12] Masdar A., Ibrahim B. S. K. K., Hanafi D., Mahadi Abdul Jamil M., Rahman, K. A. A., 2013. Knee Joint Angle Measurement System Using Gyroscope and Flex-Sensors for Rehabilitation. The 6th Biomedical Engineering International Conference, Amphur Muang, Thailand, 23-25 Oct., pp. 1-4, DOI: 10.1109/BMEiCon.2013.6687719.

[13] Bakhshi S., Mahoor M. H., Davidson B. S., 2011. Development of a Body Joint Angle Measurement System Using IMU Sensors. Annual International Conference of the IEEE Engineering in Medicine and Biology Society. Boston, MA, USA, 30 Aug.-3 Sept., pp. 6923-6926, DOI: 10.1109/IEMBS.2011.6091743.

[14] Faisal A. I., Majumder S., Mondal T., et al., 2019. Monitoring Methods of Human Body Joints: State-of-the-Art and Research Challenges. Sensors (Basel, Switzerland), **19**(11), pp. 2629.

[15] Lee S. I., Daneault J., Weydert L., Bonato P., 2016. A Novel Flexible Wearable Sensor for Estimating Joint-Angles. IEEE 13th International Conference on Wearable and Implantable Body Sensor Networks (BSN), San Francisco, CA, USA, 14-17 June, pp. 377-382, DOI: 10.1109/BSN.2016.7516291.

[16] Kim J-N., Chong W. S., Kim S-H., Kim, K., 2019. Health Management Monitoring System for Use in Classifying Lower Extremity Movements of the Elderly. Journal of Mechanics in Medicine and Biology, **19**(7), pp. 1940028.

[17] Tognetti A., Lorussi F., Carbonaro N., De Rossi D., 2015. Wearable Goniometer and Accelerometer Sensory Fusion for Knee Joint Angle Measurement in Daily Life. Sensors, **15**(11), pp. 28435–28455.

[18] Bonnet V., Joukov V., Kulić D., Fraisse P., Ramdani N., et al., 2016. Monitoring of Hip and Knee Joint Angles Using a Single Inertial Measurement Unit during Lower Limb Rehabilitation. IEEE Sensors Journal, Institute of Electrical and Electronics Engineers, **16**(6), pp. 1557–1564.

[19] Majumder S., Mondal T., Deen M. J., 2017. Wearable Sensors for Remote Health Monitoring. Sensors (Basel, Switzerland), **17**(1), pp. 130.

[20] Cooper G., Sheret I., McMillian L., Siliverdis K., Sha N., Hodgins D., Kenney L., Howard D., 2009. Inertial Sensor-Based Knee Flexion/Extension Angle

Estimation. Journal of Biomechanics, **42**(16), pp. 2678–2685.

[21] Seel T., Raisch J., Schauer T., 2014. IMU-Based Joint Angle Measurement for Gait Analysis. Sensors Journal, **14**(4), pp. 6891–6909.

[22] Qi Y., Soh C. B., Gunawan E., Low K-S., Thomas R., 2015. Lower Extremity Joint Angle Tracking with Wireless Ultrasonic Sensors during a Squat Exercise. Sensors, **15**(5), pp. 9610.

[23] Toffola L. D., Patel S., Ozsecen M. Y., Ramachandran R., Bonato P., 2012. A Wearable System for Long-Term Monitoring of Knee Kinematics. IEEE-EMBS International Conference on Biomedical and Health Informatics, Hong Kong, China, 5-7 Jan., pp. 188-191, DOI: 10.1109/BHI.2012.6211541.

[24] Fennema M. C., Bloomfield R. A., Lanting B. A., Birmingham T. B., Teeter M. G., 2019. Repeatability of Measuring Knee Flexion Angles with Wearable Inertial Sensors. The Knee, **26**(1), pp. 97–105.

[25] Papi E., Bo Y. N., Mcgregor A. H., 2018. A Flexible Wearable Sensor for Knee Flexion Assessment during Gait. Gait & Posture, **62**, pp. 480–483.

[26] Watson A., Sun M., Pendyal S., Zhou G., 2020. TracKnee: Knee Angle Measurement using Stretchable Conductive Fabric Sensors. Smart Health, **15**, pp. 100092.

[27] Bergmann J. H., Anastasova-Ivanova S., Spulber I., Gulati V., Georgiou P., McGregor A., 2013. An Attachable Clothing Sensor System for Measuring Knee Joint Angles. IEEE Sensors Journal, **13**(10), pp. 4090–4097.

[28] Othman A., Hamzah N., Hussain Z., Baharudin R., Rosli A. D., Ani A. I. C., 2016. Design and Development of an Adjustable Angle Sensor Based on Rotary Potentiometer for Measuring Finger Flexion. The 6th IEEE International Conference on Control System, Computing and Engineering, Batu Ferringhi, Malaysia, 25-27 Nov., pp. 569-574, DOI: 10.1109/ICCSCE.2016.7893640.