

Internet of Things-based telemonitoring rehabilitation system for knee injuries

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Article Info

Article history:

Received Mar 7, 2020

Revised Jul 19, 2020

Accepted Aug 4, 2020

Keywords:

Biomedical

Goniometer measurements

Internet of Things

Knee rehabilitation

Reduced mobility

ABSTRACT

Rehabilitation engineering, as one of the active research areas in biomedical science, needs further investigations and improvements. The process of rehabilitation, whether after a stroke, ligament, or accident-related injuries, is commonly based on clinical assessment tools, which can be executed, either by self-reported (home-based) treatment or through observer-rated therapy. However, people with reduced mobility (*e.g.*, stroke, surgical, and ligament patients) can benefit from rehabilitation programs only if effective and appropriate assistive tools are provided. In this paper, a new Internet of Things (IoT)-based telemonitoring system is introduced for knee injuries' rehabilitation (Knee-Rehab). The proposed system is a real-time rehabilitation and monitoring framework designed to be a portable, home-based, and online-based instrument comprised of bio-mechanical, bio-instrumentation and IoT-based elements. The system helps patients to rest at home after surgeries or physical treatment, do their rehab-exercises, and receive suggestions from their advisors, which gain the ability to monitor the situation over the exercising time and propose necessary medication/activities to be followed by the patients accordingly, based on their current status. The experimental measurements show the high accuracy achieved by the developed system in terms of monitored knee joint angle, where the maximum error is 3.5° compared to manual goniometer measurements.

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1. INTRODUCTION

The purpose of rehabilitation is to restore back the normal physical movement of any part of the human body that has been lost due to a stroke or any accident-related injury [1], [2]. The process depends on using clinical assessment tools and can be done either as a home-based self-treatment or through an observer-rated method at the rehabilitation center [3]. The later can be time-consuming and cost-intensive. The patients are required to do their exercises at the rehabilitation center frequently under observations over the treatment time. In addition, patients living in remote and rural areas may have limited access and face difficulties in

attending rehabilitation centers, which advise them to come back and forth periodically. Further, problems encountered at the time of occupational therapy interventions, quality of the material itself, and the level of patient ability to recover, may impose an extra cost. Thus, such limitations of the observer-based rehabilitation model need to be addressed and considered when developing new rehabilitation tools, so as to provide time-flexible, cost-effective and affordable rehabilitation assistive product.

The home-based rehabilitation system is an exceptional solution to overcome such limitations. It allows patients to rest at home after surgeries or physical treatments, do the rehab-exercises as a self-treatment, and follow instructions given by their remote observers immediately. The Internet of Things (IoT) is a communication paradigm that envisions total connectivity with objects of everyday life and is an integral part of the internet infrastructures [4], [5]. In recent years, the emergence of the IoT has brought about tremendous technological changes [6]-[9], especially with the current trend towards smart cities and smart buildings. Some examples are the smart wearable tracking kid's system in a smart building, and human motion wearable tracking system for healthcare application [10]. Rehabilitation and elderly monitoring for active aging can benefit from IoT capabilities, particularly, for in-home treatments [11]-[13]. The observer can monitor the situation continuously in real-time, propose necessary medications, and suggest appropriate activities based on the patients' conditions and limitations. Athletes, for example, may encounter several injuries including, knee fracture, anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), or any other type of ligament injuries [14]. Therefore, rehabilitation tools should be capable to help in recovering from such problems, reducing the muscle stiffness, and supporting a range of motion (for example, hip and knee flexion) [15].

In the last few years, a number of IoT-based solutions for knee monitoring systems have been suggested. Golgouneh *et al.* [16] have proposed a lighter, portable, and adjustable continuous passive motion (CPM) machine with a user-friendly interface. An android-based application is used for interaction between users and the introduced tool so that data can be stored and recorded in the patient's smartphone via Bluetooth communication. Thus, the patient can use this new machine for adjusting her/his leg movement without any external help compared to the traditional CPM machine which is bulky, heavy, and expensive. In [17], a mobile application is developed by Gay *et al.*, as a monitoring method that keeps tracking of the patient's progress, reports the current status of the rehabilitation process to the health professional, and provides patients with immediate feedback accordingly. The inconvenience of this platform is that the patient/user needs an actual description of the pain amount based on feeling. In addition, their evaluation procedure does not refer to any practical measurements, implying an inaccurate outcome of the study. In [18], Bonnet *et al.* developed a pseudo-online 3D estimation scheme of the hip, ankle, and knee joint angles of patients through an automated system. Nevertheless, the work is limited to five types of rehabilitation exercises, which should be performed in a standing mode. Also, the results of measurement are not accurate in practice as all the values should be calculated by the proposed algorithm itself. In [19], Tu *et al.* designed a new system for lower limb rehabilitation, hip-knee-ankle. They used an integrated system, which composed of low-cost hip-knee exoskeleton prototype, functional electrical stimulation (FES), and chattering mitigation robust variable control (CRVC) algorithm. Their aim was to minimize the cost and design complexity of the hip-knee-ankle exoskeleton. However, such a system seems to be complex for patients' clinical treatment due to the huge size and bulky device. The authors used more than a technique to produce experimental results. Ferriero *et al.* [20] presented a comparative study of two different methods of knee angle measurements: DrGoniometer (DrG) and Universal Goniometer (UG). The study has been done to evaluate the reliability of a developed application based on a smartphone, and is used for joint goniometry assessment of clinical rehabilitation. However, the angle measurement process did not include a sensing unit, meaning that the measurement is not practical. In [21]-[29], wireless surface electrical stimulator systems have developed to measure the knee angle using wearable sensor technology, in which they used a pair of flex sensors attached to a supportive cloth worn by the patient. However, the measurement process in their study needs a physician's attendance to help the patients on exercising required activities. In addition, the dislocation of the patient leg during the rehab-exercise may affect the patient's healthcare and injured knee healing process [21]. People with mobility limitations can benefit from rehabilitation programs, particularly, if an appropriate rate of medicine is provided for the patient after surgery, stroke, or ligament injuries. Therefore, in this paper, we develop a portable home-based knee rehabilitation tool along with an online monitoring system. Our innovative apparatus integrates biomechanical, bioinstrumentation and IoT-based techniques. The aim is to introduce an accurate, reliable, and flexible mechanism for effective patient recovery compared to the traditional systems.

2. REHAB-SYSTEM ARCHITECTURE

In this section, a detailed description of the designed architecture of the Knee-Rehab system is provided, and each subsystem is critically analyzed. The Knee-Rehab system contains nine individual parts/subsystems attached

together to form the desired model. For each subsystem, we discuss six main factors (including technologies, dimensions, cost, performance, safety, materials, and competitive setting), which impact its functionality. The designing process is achieved as in the following steps. First, a convenient and user-comfortable prototype has been created through hand-drawing, while considering all the major parameters such as height, weight, strength, adjustability, and sustainability. Then, SolidWork software has been used to sketch the created draw in order to finalize mechanical tools to be used by humans. The designed model is shown in Figure 1. This model, then, is converted into a 3-D view from the different sides as shown in Figure 2.

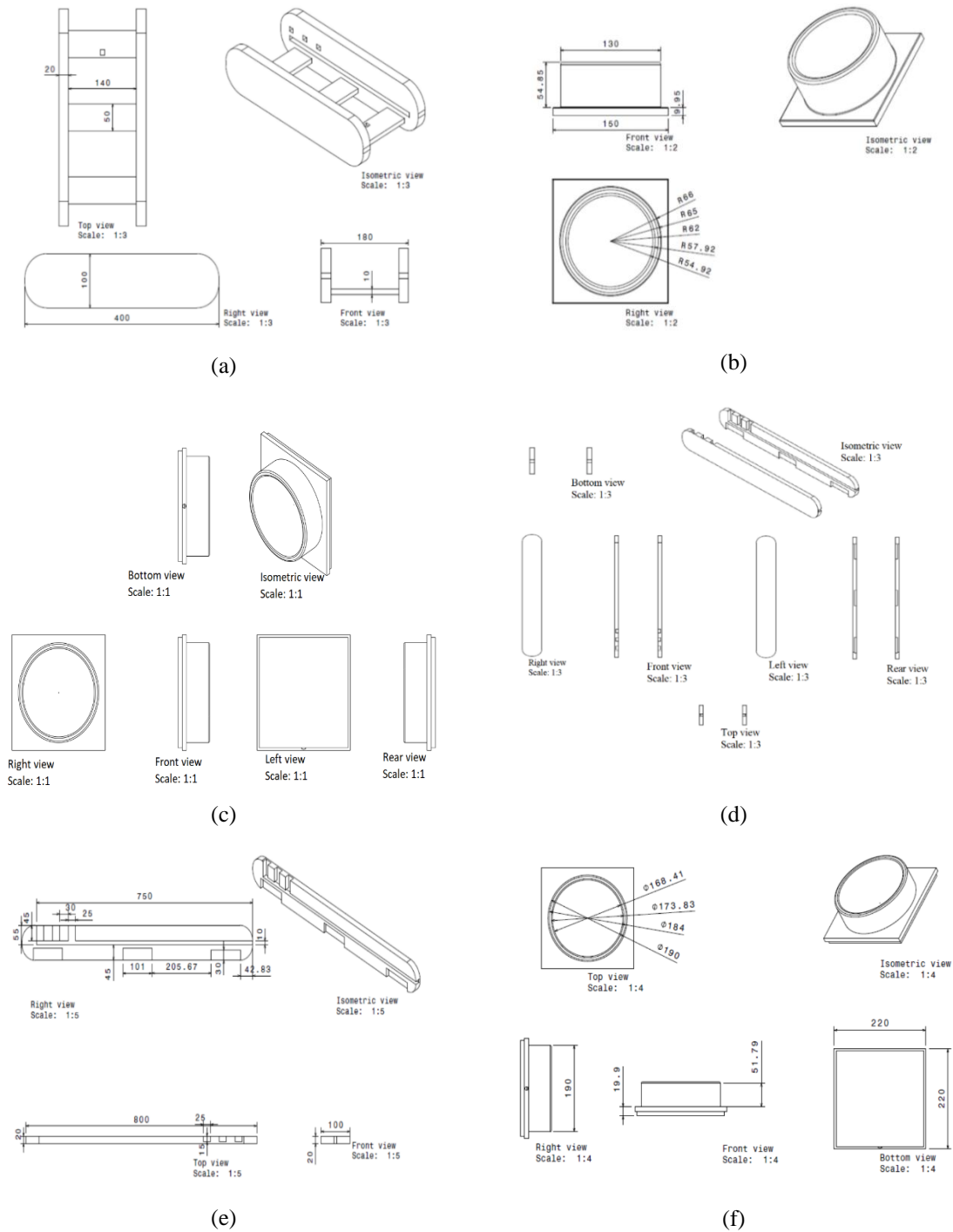


Figure 1. The designed model: where (a) Illustrates the system design as a full piece and shows the diameter between sides, (b), (c) and (d) Show the hole place basic design with a slider and its measurements, (e) and (f) Show basic sketches of all the sides, along with measurements of all the details included

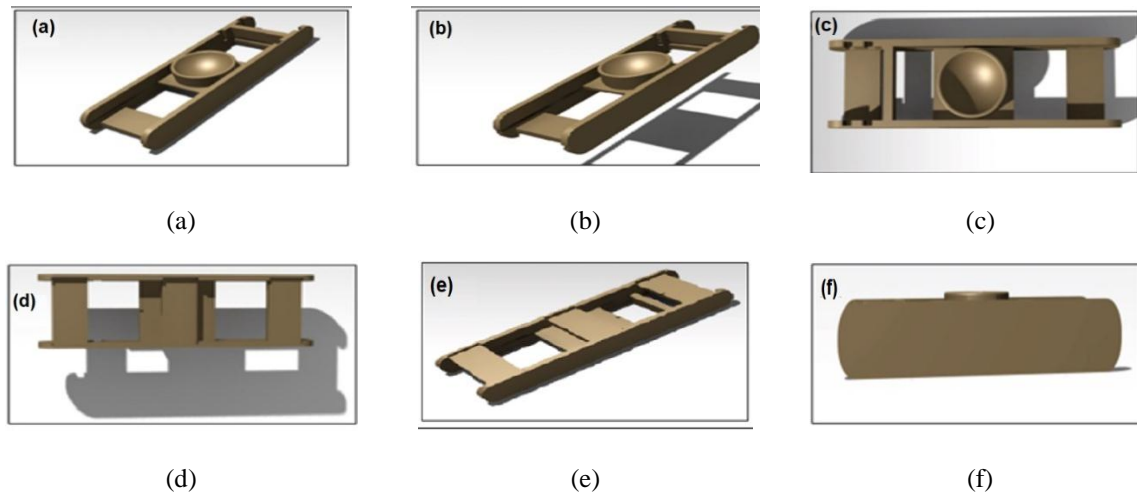


Figure 2. The 3-D side views from different angles: (a), (b) and (c) Show the top view of chassis, (d) and (e) Show the back-bottom view, while (f) shows the side view

The design attributes, such as size, length, and width of the frame, are taken based on appropriate dimensions to facilitate activities of knee rehabilitation. Also, the type and quality of materials have been taken into account. We have done necessary calculation to choose different types of materials based on the patient force as well as the strength and weight of the material itself. Thus, all the system parts (such as chassis) were made of strong and lightweight stuff that can withstand heavy-weight, force, and pressure imposed by the patient when using Knee-Rehab. At the same time, the system can be easily carried by the rehab-user.

Figure 3 shows the system block-diagram, which includes a wooden chassis, two units of flexible sensors (FS1 and FS2), and a microcontroller unit (Arduino UNO) connected to a Wi-Fi shield. The microcontroller unit reads the data of knee joint movement using flex sensors, and sends this data through WiFi module to the online Thikspeek cloud. The process starts at the hardware parts, in which the chassis is used to train the patient, the Arduino reads (i) the bending angle from the flex sensors in terms of degree, and (ii) the number of patient movements per round of activity from LDR sensor, and, then, data is sent to Thikspeek on internet through WiFi unit. Thikspeek online platform shows the whole operations of the knee monitoring rehabilitation system, which allows physicians to read data and analyze patient’s improvement so as to make the right decision in real-time. The patients, also, can see their improvement level in the LCD display.

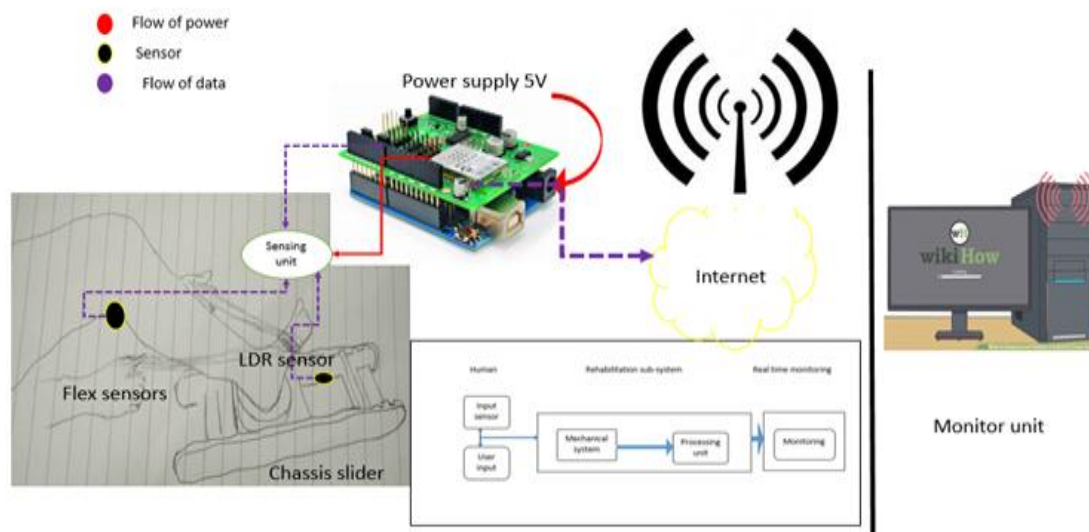


Figure 3. The block diagram of the proposed system

The system includes two units of 4.5-inches flex sensors placed on a supportive cloth worn by the patient under testing progress as shown in Figure 4, and a light dependent resistor (LDR) sensor placed on the mechanical chassis. A portable and adjustable mechanical slider made of wooden material is connected to the light-sensitive LDR sensor to count the number of moves per active round. In addition, a resistance band should be held by the patient for limb movements. When the body joint moves or flexes, the resistivity of the flexure sensor changes, which can be mapped to the angle between the joints through post-processing. In some applications, such as monitoring the progress of body joints after surgery, precise angles are less important than consistency of measurements over time. Further, the change and development of joint flexion are more critical than the accuracy of the joint angle. We model the behavior of joint motion over time and use this model in a real-time rehabilitation monitoring system to obtain measurements from wearable sensors. Thinkspeak platform has been used for online data monitoring in the proposed system.

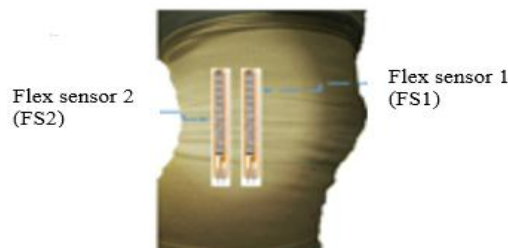


Figure 4. The positions of two flex sensors

3. RESULTS AND DISCUSSION

The final prototype for the designed system is shown in Figure 5. On the Figure 5(a), the figure shows a well-equipped system with all the developed parts, while on the Figure 5(b) it shows how the patient is using the device. For evaluating the designed prototype, several tests have been conducted on normal users as well as patients. At the first stage, the developed system has been tested on four normal (healthy) users to ensure the functionality of the entire system before sending it to the clinic for actual use by patients. Figure 6 shows the results (knee angle measurements) from using the prototype by normal users with different activities. Table 1 illustrates the maximum, minimum and average bending values measured from FS1 and FS2 for each user. The average difference between the readings data from FS1 and FS2 for User1, User2, User3 and User4 are 10.6° , 0.63324° , 0.904° , and 9.3° , respectively. The recorded large differences show clearly the purpose of using two flex sensors since they are not too accurate. By taking the average of the data read from FS1 and FS2, the error is significantly reduced into less than 4° , which is considered very small value as it represents an invisible bend in the knee. Therefore, the proposed system can be used efficiently for monitoring patients' condition and provides sufficient motivation. In addition, the system can be used to assess rehabilitation progress.



Figure 5. The prototype under using condition, (a) Equipped system, (b) Patient is using the device

Furthermore, additional experimental tests have been conducted to ensure the prototype functionality when applied to actual patients. In this experiment, we have performed three tests on four patients. The flexible sensors were connected to the Arduino UNO to collect the measured data. Table 2

shows the results for each individual test and user in term of average measured bending angles. To compute the exact measurement error, we compared the obtained results with that of using goniometer manual measurements. The manual results using goniometer are tabulated in Table 2 for each individual test. From this table, it is clear that the limits of bending are almost between 40 to 70 degrees. This illustrates that the tests have been done to those who do not have serious injuries in their knees. It, also, indicates the ability of the measurement system to read the bending angle in different positions with closer values, and how the integrated sensors are working together with a minimum recorded error, *i.e.* 3.5° at maximum. According to the results in Table 2, it can be seen that the average angle values for the four patients are different. This is because that each user is different in size and shape. Hence, this proves that the developed device is so flexible that it can be worn and used by anyone.

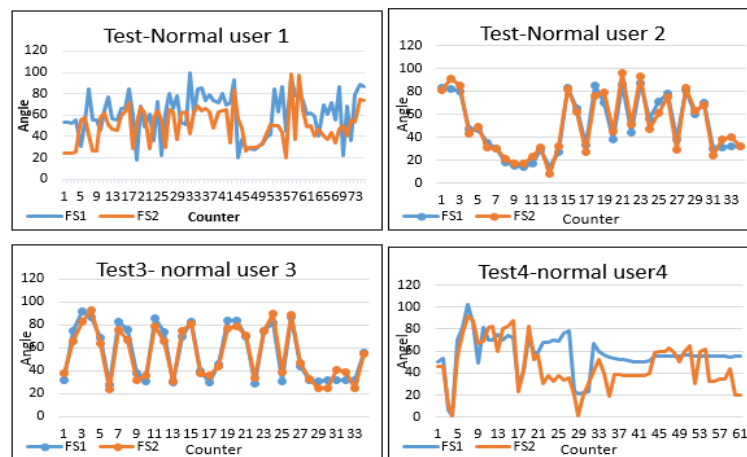


Figure 6. Results of testing the integrated system with a normal user

Table 1. The obtained data from FS1 and FS2 sensors for different users' activities

| | User1 | | User2 | | User3 | | User4 | |
|---------------------------------|-------|-------|---------|-------|-------|-------|-------|--------|
| | FS1 | FS2 | FS1 | FS2 | FS1 | FS2 | FS1 | FS2 |
| Maximum bend (°) | 100 | 97 | 87.6 | 95.76 | 92.04 | 93.42 | 102 | 92 |
| Minimum bend (°) | 22 | 29 | 14.2 | 8.9 | 31.5 | 23.4 | 1 | 1 |
| Average bend (°) | 60.9 | 50.32 | 50.3747 | 51.01 | 55.91 | 55 | 56 | 47.148 |
| Average readings difference (°) | 10.6 | | 0.63324 | | 0.904 | | 9.3 | |

Table 2. Results obtained from the designed Knee-Rehab assessment device and goniometer

| | Patient 1 | Patient 2 | Patient 3 | Patient 4 |
|---------------------------------------|-----------|-----------|-----------|-----------|
| Test 1 average | 41.7° | 49.45° | 48.63° | 48.37° |
| Test 2 average | 51.09° | 54.9° | 59.71° | 52.92° |
| Test 3 average | 58.78° | 69.71° | 69.35° | 66.02° |
| Average bending angle for three tests | 50.523° | 58.02° | 59.23° | 55.77° |
| Goniometer manual measurement | 53° | 55° | 60° | 57° |

Besides its core functions, which are patient rehabilitation, and measuring the knee bending angle, our introduced system can also work as a monitoring device. The data from the microcontroller can be sent online to therapists. For users themselves, they can monitor their improvements during the physiotherapy session through the data appeared on the LCD display as a real-time feedback. This gives them an empirical benchmark so that they know the level of improvement at which they reached, either they are in a good condition or not. In Figure 7, we can see three different values on the LCD display. In the first line, the value represents the movement number, which is the result of the LDR sensor; while in the second line, the values, A1 and A2, are the measures of bending angles from FS1 and FS2 sensors, respectively. Figure 8 shows the online monitoring system using ThinkSpeak platform. The monitored data as shown has been collected, processed, and transferred by sensors, processor, and Wi-Fi module respectively. This cloud platform allows specialists to monitor the results at any time and make the appropriate decision based on the analyzed data. All the collected data has been used as an indicator to evaluate the progress of knee rehabilitation exercise. To do that, three tests have been performed on three different patients and the improvement amount is computed using (1).

$$Abd = (LAt - FAt) \quad (1)$$

where Abd is the average bending improvement in degree, LAt is the average bending on the last test, and FAt is the average bending on the first test.

Table 3 shows the calculated average of patient recovery. It is obvious that the ability of recovery is improved after a short exercise. In addition, the system has an acceptable accuracy to be used as a knee rehabilitation device. By comparing the results obtained from the manual goniometer to that measured by the developed system, as shown in Table 2, it is observed that the sensitivity of using two flex sensors is high and the error is tiny. The maximum error was only $\pm 3.5^\circ$ of the actual angle.

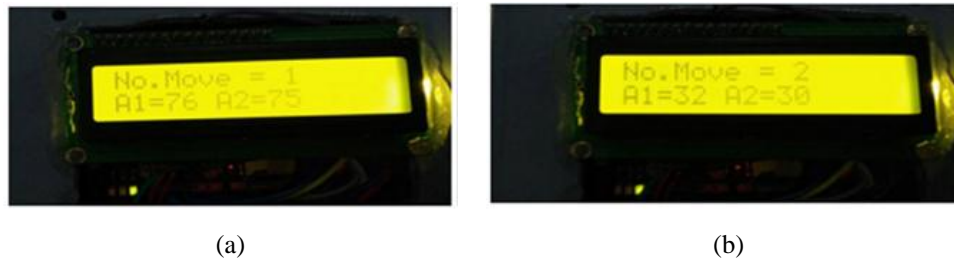


Figure 7. System output on LCD display shows the reading values from the two flex sensors while, (a) The knee is bend, (b) Straight

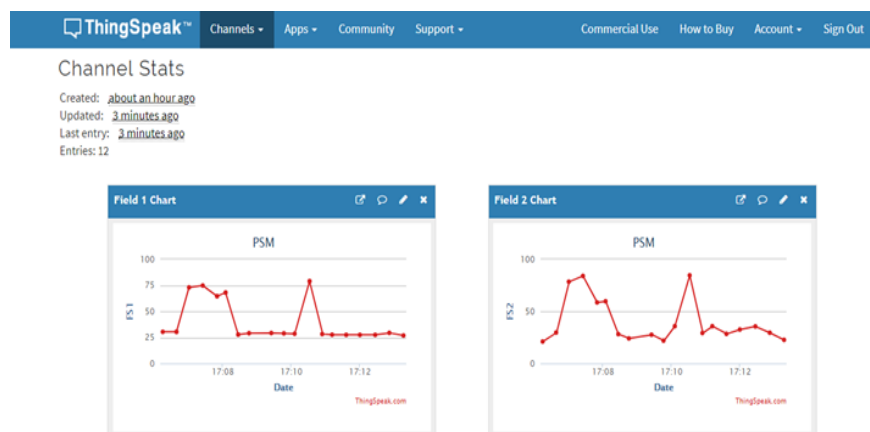


Figure 8. Online monitoring system using *ThinkSpeak* platform

Table 3. The average of patient recovery

| User | Patient 1 | Patient 2 | Patient 3 | Patient 4 |
|--|----------------|----------------|----------------|----------------|
| Average recovery over time in ($^\circ$) | 17.08 $^\circ$ | 20.26 $^\circ$ | 20.72 $^\circ$ | 19.63 $^\circ$ |

4. CONCLUSION

In this paper, we have developed an IoT-based knee rehabilitation and monitoring system that benefits patients to recover from consequences of various knee injuries. The major goal is to make the rehabilitation process more accurate, flexible, and effective in terms of time and cost. The system consists of a number of subparts (*i.e.*, bio-mechanical, bio-instrumentation, and IoT-based parts), integrated together to form a home-based portable assistive device. Several experiments have been conducted for evaluating the integrated system with different patients, having different situations and activities. The measurement values indicate that our system is able to accurately read the bending angle in various placements with a maximum error value equal to 3.5° compared to the manual goniometer measurements. The experimental outcomes show satisfying results that denote the superiority of our rehabilitation system compared to conventional models. This implies that our provided rehabilitation system is reliable and efficient enough to be used by different users under any conditions. This helps patients to do their rehab-exercises at home while receiving feedback from their advisors immediately. The advisors can remotely monitor the patient rehabilitation process in real-time through the introduced monitoring system, which uses ThinkSpeak online cloud. They can read the collected

data sent from rehabilitation device to the online monitoring system, analyze this data, and send their recommendations to be followed by patients based on his/her current condition. The proposed system overcomes the limitations of the observer-rated therapy model, in which the treatment is done at the rehabilitation center. Thus, the patients can be afforded a portable, lightweight, reliable, and easy to use rehabilitation tool while keeping in contact with their observers continuously during the treatment period.

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