Comprehensive Musculoskeletal Care Platform Enabling At-home Patient Care

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Abstract: Pain and stiffness in the musculoskeletal system cause limited range of motion and loss of mobility. Remediation includes home care programs, physical therapy, medication, and if necessary, surgery. Much of the recovery occurs at home. Active engagement by patients in their care program is crucial for successful clinical recovery. Recovering from a partial or total joint replacement requires active participation in an exercise program to help minimize swelling and improve motion and strength. On the other hand, non-surgical musculoskeletal indications, also require a personalized exercise plan for recovery. Patients need support with following their care at home. Remote care programs and monitoring offer convenient, safe, and time and cost-efficient care, including at-home physical therapy programs, and have broad clinical scope. We studied one such program. This paper reports the results of a platform that digitizes care programs for all musculoskeletal conditions, engages patients at their convenience, while providing visibility to recovery progress via patient-reported and sensor-generated data. We introduce Plethy Recupe which is a comprehensive platform for musculoskeletal care with a joint motion sensor, intuitive app, and intelligent clinical dashboard. Six exercises were selected from this platform and 10 individuals were asked to perform the exercises to evaluate the accuracy of the range of motion (ROM) and complete a questionnaire on the usability of the solution.

1 INTRODUCTION

The rehabilitation process is crucial for recovery after major surgical procedures and for the management of chronic conditions. Rehabilitation exercises may also be performed prior to surgery. This is known as pre-habilitation and is also thought to effectively improve postoperative functional performance and strength gain (Topp et al., 2009). Typically, the rehabilitation process involves many in-person, one-on-one sessions with a physical therapist. In between these regular sessions, the patient will be expected to repeat rehabilitation exercises at home, unsupervised. In order to get further feedback on their performance, the patient will have to book another appointment with his/her physical therapist. This takes up the limited time of the physical therapist, requires means to travel to and from their office, and can be costly. This process is thus time and labor-intensive. It is estimated that as of 2019, there were 2.4 billion people globally with a condition that would benefit from rehabilitation and that the need for rehabilitation worldwide will increase over time (Cieza et al., 2020). Remote monitoring of physical training sessions can improve both the efficiency and effectiveness of this care.

Remote monitoring is convenient, safe, and time and cost-efficient. (Tack, 2021) In addition, it offers improvements to the quality of care that patients receive. Patients can be monitored more frequently, can receive objective, real-time feedback on their performance, and will have a record of consistent, thorough data from their exercise sessions. The solution we choose to study was Plethy Recupe, a comprehensive system for remote care focused on all musculoskeletal conditions. The system consists of a wearable sensor, an intuitive phone application, and a dashboard for the healthcare provider.

The sensor is simple, small, and versatile. While other remote patient monitoring systems achieve finer

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granularity through a more complex, multi-sensor system (Lorussi et al., 2018) (Ramkumar et al., 2019), the singular Plethy Recupe sensor prioritizes ease of use by patients at home. This simple setup reduces inaccuracies due to user error and is neither intimidating nor discouraging to a broad spectrum of patients. Other work in the field of remote rehabilitation has also used the entire phone as the sensor itself (Chomiak et al., 2019). The Plethy Recupe sensor is only a little larger than a quarter, making it easy to wear and unobstructed while exercising. Other research specializing in remote monitoring of knees has also used sensors that are embedded in a wearable knee sleeve (Ramkumar et al., 2019). By using a sensor that can be attached to different locations, the Plethy Recupe solution can be used for various joints. In addition to the knee, the sensor can be used for the ankle, hip, lower back, shoulder, elbow, and wrist, etc. This also allows for future expansion of the Plethy Recupe system to other regions, surgeries, and conditions.

The phone application is compatible with both iOS and Android, making Plethy Recupe accessible to nearly any patient with a smart device. The app is designed to be straightforward and helpful for patient motivation and recovery. It includes video demonstrations of how to perform exercises, training videos on sensor placement, and live visualization of the patient's range of motion. In addition, it counts successful repetitions of an exercise in real-time and generates range of motion measurements. Upon start-up, it surveys patient symptoms, level of pain, reminds patients when to exercise, when to take medications, and of upcoming surgery-related events. All of this data is available to the clinician as well.

The remainder of the paper is structured as follows. Section 2 provides the requisite background on importance of musculoskeletal conditions. Section 3 discusses the system specification of the Plethy Recupe, including hardware implementation, exercise recognition algorithm, mobile application, and clinical dashboard. Section 4 introduces the six exercises that are evaluated in the experiments. Section 5 presents the result of the experiments and preliminary evaluation of the Plethy Recupe. Finally, we conclude and propose our future research direction in Section 6.

2 CLINICAL BACKGROUND

The World Health Organization names musculoskeletal conditions as the leading contributor to disability worldwide. There are over 150 diagnoses which qualify as musculoskeletal, affecting the joints, bones, muscles, spine, and connective tissue. (World Health Organization, 2021) These conditions are highly prevalent and cost our society a large sum in both treatment costs, lower quality of life, and loss of income due to inability to work. In the United States in 2018, one out of two adults were diagnosed with a musculoskeletal condition, totaling $124 million people (Bone and Joint Initiative, 2018). Through direct and indirect costs, musculoskeletal disorders cost the United States $150 billion and are expected to increase by $73 between 2014 - 2024 (Optum, Inc., 2019). As such, musculoskeletal pre-rehabilitation, treatment, and rehabilitation are of high importance to the well-being of society and economy.

In this study, the focus is on musculoskeletal exercises intended to strengthen the knee and ankle joints, as arthritis in the knee is the most common musculoskeletal indication. Each exercise in the app includes a brief description of how to perform it along with a video demonstration. The six exercises tested are Long Arc Knee Extension, Heel Slides with Quad Sets, Toe Raises, Reverse Toe Raises, Ankle Pump, and Seated Ankle Pump. The first two exercises target muscles that support the knee and the remaining four strengthen the ankle. For example, the Long Arc Knee Extension exercise strengthens the quadriceps muscles which support the range of mobility of the knee.

It is estimated that in 2010, 1.52% of the United States population underwent total knee replacement surgery. This is approximately 4.7 million individuals (3.0 million women and 1.7 million men) who had this procedure done. These numbers only account for those who had total knee replacement surgery. In addition, there are millions of people with partial surgeries or musculoskeletal conditions that arose for other reasons such as overuse or traumatic impact. Musculoskeletal problems in the foot and ankle are experienced by approximately 1 out of every 5 people. Further, it has been found that the number of total ankle replacement surgeries performed in the United States increased by 261% from 2005 to 2014. In this same time period, ankle fracture surgeries increased by 82% (Burton et al., 2020). As such, the development of a rehabilitation program with exercises for knee and ankle recovery like the ones tested here is crucial and increasingly critical.

3 MATERIAL AND METHODS

The Plethy Recupe Solution is composed of three main components: a wearable sensor, a smartphone application, and a clinical dashboard as in figure 1. The sensor unit is designed to measure the range of

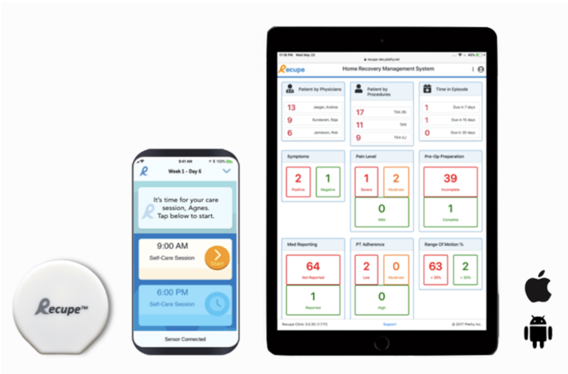

Figure 1: Components of the platform: a sensor unit, linked smartphone application, and clinic dashboard.

joint angle movement using an IMU. It is mounted on a casing that's easy to wear and attached to any part of the body using a reusable adhesive. The sensor unit is programmed with different algorithms to count the number of successful repetitions along with the range of movement angle for each exercise. The readings of the sensor unit are transmitted to an application via Bluetooth. The application stores the recordings in the cloud-based database along with the number of successful repetitions. It also displays the number of care sessions including the home exercise program. The dashboard enables the healthcare provider to monitor the patient's functionality and progress throughout the entire care journey (pre-surgery to post-surgery) or the non-surgical treatment process.

3.1 Hardware

An Inertial Measurement Unit (IMU) has been utilized to measure the joint angle and count the number of repetitions per exercise. It is a 9-axis motion tracking device that incorporates a triple-axis gyroscope, a triple-axis accelerometer, and a triple-axis magnetometer all integrated into a Quad Flat Noleads (QFN) package. The IMU precisely offers full 9-axis Motion Fusion performance with its dedicated I^2C sensor bus. It involves a total of nine 16-bit analog-to-digital converters (ADCs) for 3-axis gyroscope, 3-axis accelerometer, and 3-axis magnetometer output digitization. In this work, three vibratory MEMS rate gyroscopes are used, which detect rotation around the 3-axis, and acceleration around a particular axis that causes displacement on the associated proof mass with a measurement range of up to $\pm$ 16g. The Coriolis effect (McDonald, 1952) induces a vibration detected by a capacitive pickoff while the gyroscope is rotated along either of the axes. Then, a voltage that is proportional to the angular velocity is generated. This voltage is digitized using 16-bit ADCs with a range of up to $\pm$ 2000 degrees per second (dps).(Invensense TDK, 2021)

The IMU data is transmitted to the phone application via Bluetooth 5 connection. The Bluetooth module communicates with the IMU via I^2C bus at 400 kHz frequency. Low energy consumption, small area requirements (a $6.5mm \times 6.5mm$ package), and simplified development costs of this module make it perfectly fitted for wearable devices.(Silicon Labs, 2017)

The system chip is equipped with a square TACT switch with no stem on it (ALPS, 2021) and a through-hole mount battery holder that provides solid electrical contact for a lithium coin battery. They are all housed in an $18mmDia \times 9mmH$ Recupe package. The housing consists of a bottom and a cap which are detachable in case the battery has to be replaced and they can be coupled afterward. With a little press on the housing, the sensor starts connecting to the paired smartphone with a blinking blue light. The sensor is automatically turned off after 15 seconds if it cannot find the paired phone and have a successful connection via Bluetooth. This can occur if the Recupe application is closed on the smartphone, or if the smartphone is out of the sensor range. The sensor blinking green light confirms that it is successfully connected to the smartphone.

3.2 Algorithm

In order to count the repetitions per exercise, the algorithm properly fuses Gyroscope and Accelerometer inputs. The confidence on each sensor can be configured independently. With the help of sensor fusion, the strengths of the gyroscope and accelerometer are obtained and the effects of weaknesses in each are mitigated. The algorithm accounts for calibration of gyroscope signal and accelerometer, and post-processing of algorithm output. In this algorithm, angular velocity is also considered as a metric.

The gyroscope model is as in equation 1, where ω is the true angular velocity, b is bias, and σ is additive zero-mean Gaussian noise. The static bias can be calibrated out. The white noise is mainly due to the nature of the sensor.

$$\tilde{\omega} = \omega + b + \eta, \qquad \eta \sim N(0, \sigma^2_{gyro})) \quad (1)$$

The equation 2 is used to calculate the orientation resulting from the gyroscope measurements. This equation is the result of applying Taylor expansion to gyroscope measurements.

$$\theta(t+\Delta t) \approx \theta(t) + \frac{\partial}{\partial t}\theta(t)\Delta t + \varepsilon, \qquad \varepsilon \sim O(\Delta t^2) \quad (2)$$

Given $\theta(t)$ which is the angle at last time step, $\frac{\partial}{\partial t}\theta(t) = \omega$ which is the gyro measurement(angular velocity), Δt which is time step, and ε which is approximation error, we seek $\theta(t+\Delta t)$ which is the angle at current time step. When the sensor is used for long periods, the approximation error leads to drift. Since the duration it takes to do an exercise is short, it can be neglected.

Linear acceleration is measured by equation 3. With the accelerometer in a stationary position, the linear acceleration results in the noisy gravity vector, $a^{(g)}+\eta$. The direction of this vector is pointing up with magnitude 9.81 $m/s^2 = 1g$. However, any acceleration yields the linear acceleration to a combined vector of external forces,$a^{(l)}$, and noisy gravity.

$$\tilde{a} = a^{(g)} + a^{(l)} + \eta, \qquad \eta \sim N(0, \sigma^2_{acc})) \quad (3)$$

Equation 4 relates the roll and pitch angles to the normalized accelerometer readings. Depending on the rotation sequences this matrix might hold different row ordering.

$$\hat{a} = \frac{\tilde{a}}{\|a\|} = \begin{pmatrix} -\cos(-\theta_x)\sin(-\theta_z) \\ \cos(-\theta_x)\cos(-\theta_z) \\ \sin(-\theta_x) \end{pmatrix} \quad (4)$$

By solving equation 4, the roll and pitch angles are computed. A challenge to be addressed is that at multiples of 2π, the equations for the roll and pitch angles have an infinite number of solutions. It is somewhat beneficial to limit the range of the roll and pitch angles to fall in the range of $-\pi$ to π, but it still leads to two distinct roll and pitch angle solutions. The solution is to limit either the angle of the roll or the angle of the pitch to lie in between $-\frac{\pi}{2}$ to $\frac{\pi}{2}$. In this work, the role angle is restricted to $-\pi$ to π, and the pitch angle is ranged between $-\frac{\pi}{2}$ to $\frac{\pi}{2}$.

The aim of this work is to be able to accurately estimate 3D orientation using accelerometer and gyroscope data. To better estimate orientation, roll and pitch angles that are estimated from accelerometer data are fused with the gyroscope angle.

After calibrating gyroscope data by removing the static bias from it, incorporating the output of the gyroscope to turn the angular velocity into an angular location, applying a low pass filter to the accelerometer data to eliminate the noise in the output, and finding the accelerometer roll and pitch angles; the sensors' data can be fused by equation 5. Alpha is a constant weight that needs to be adjusted and Theta is a single state orientation.

$$\theta^{(t)} = \alpha(\theta^{(t-1)} + \tilde{\omega}\Delta t) + (1-\alpha) - (\hat{a}_z, \sqrt{a_x^2 + a_y^2}) \quad (5)$$

Velocity information is taken into consideration as well. Velocity is calculated as the integration of accelerometer results fused with the raw gyroscope data. Calculating the angular velocity gives us additional metrics to characterize exercises.

Once the algorithm generates the orientation signal, a moving average filter is implemented to smooth the output. The moving average filters the output depending on the frequency of the data stream. Among the Theta and velocity signals, we choose the one that is appropriate depending on the exercise. Then the chosen signal might need to be shrunk or expanded to output the correct angle reading which can be achieved by multiplying to a constant parameter, Gamma. Finally, after selecting the proper filtered signal and scaling it, the number of peaks in the signal are counted by setting correspondent threshold angles per exercise.

Twenty individuals were asked to do 2 sets of 10 repetitions for each exercise and a brute force search was run to find the best Alpha (fusion weight parameter), Gamma (scaling signal parameter), and best-fitted threshold angles for the counter.

3.3 Application

The application is both Android and IOS compatible. The Bluetooth connection status can be checked at the bottom of the Application screen. Before turning the sensor on, it shows ”Searching for Sensor”. By clicking the sensor on, the connection status updates to ”Sensor Connecting”. As soon as the sensor connects to the app via Bluetooth, the care sessions associated with the patient are displayed on the screen. The appearance of a blinking green light on the sensor, sig-

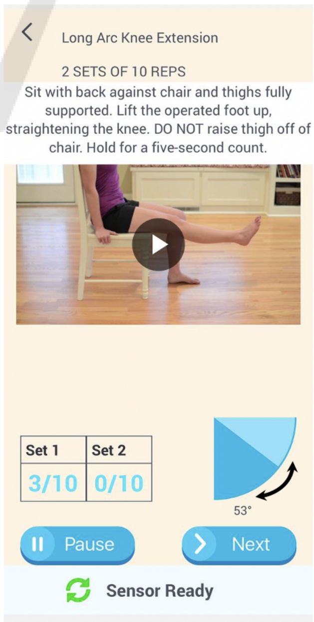

Figure 2: Application screen for a sample home screen.

nals that the connection is established, the connection status at the bottom of the screen changes from "Sensor Connecting" to "Sensor Ready" as well. Relevant pre-surgery and post-surgery exercise program is selected by the patient's orthopedic surgeon and is included in the care session of the patient. Before starting the program exercises, the patients are asked about their pain level. The care sessions are easy to follow and each of the home exercises that appears on the care session screen includes text and video instruction on how to correctly do the exercise. Figure 2 shows the screen of the application including a sample exercise, Long Arc Knee Exercise. When the sensor is stable, the start button in the bottom left corner activates. By selecting the start button, it turns into a pause option to allow patients to pause the exercise if they need to. The number of sets and repetitions per set is determined by the patient's doctor. In Figure 2, there are 2 sets of 10 repetitions for Long Arc Knee Exercise. The gauge at the right bottom of the exercise screen tracks the angle measurements in real-time. Whenever a repetition is successfully completed, the table at the left bottom of the exercise screen updates the repetitions.

The application records the medications that the patients take and once the patients complete their exercise program, the application reminds them to take their medications.

Moreover, patients' symptoms are checked daily through a survey by asking them about how they feel compared to the last care session, how their exercises go through the session, what their current pain level is, and what they feel about their Recupe program. The application assesses patients to follow their icing and elevation instructions throughout the day and to track their icing time by an ice countdown.

3.4 Dashboard

Plethy Recupe enables the patients' care team to track their progress and contact them as needed. Clinicians can track patients' progress while they manage their care plan at home. The Plethy Recupe clinical dashboard gives clinician and Recupe team authorized access to the library of exercises and patients' accounts. They can monitor patient's pain level, medication, symptoms, physical therapy adherence, range of motion percentage, pre-operation checklist, and their elevation and icing. Figure 3 illustrates the look of a patient's account. Access authorizers may modify the pre-operation and post-operation exercises per patient and the number of daily repetitions for each exercise. Moreover, they can write notes and activity reports to their patients, set an appointment for them,

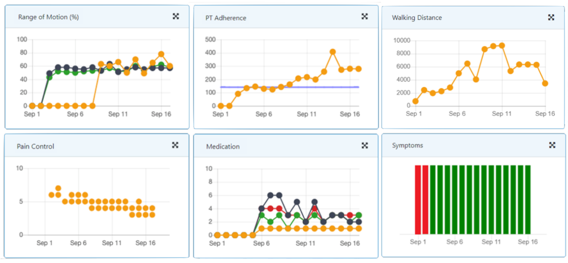

Figure 3: Sample screen from a patient account in dashboard.

check the surveys that patients have filled out, schedule their daily medications, and manage the instructions and checklists of pre-operation, post-operation, and non-surgical programs. The Plethy Recupe care team monitors the battery level of devices and notify patients to exchange the battery of their device if they need to. Registering the demographic characteristics of a new patient, an account will be added to the patients' list. Then, clinicians can create a template from the existing exercises in the library and assign it to the account. There exist hundreds of exercises in the library and it's possible to add a new exercise to the library along with the exercise description and instruction video. The parameters and threshold angles associated with the algorithm for the exercise are set in the exercise dashboard profile. Furthermore, in the exercise dashboard profile, its number of repetitions, the duration, and hold time per repetition are all defined.

4 CLINICAL APPLICATION

The system has been tested on 10 healthy subjects, 1 female and 9 males with an average age of 53. They were asked to do 6 exercises and fill out the user satisfaction survey that has been approved by our expert clinicians. The participants are expected to complete 2 sets of 10 successful repetitions for each exercise. They have been instructed on how to use the platform and where to place the sensor regarding each exercise. The exercises are as follows:

- **Long Arc Knee Extension**, participants are asked to sit with their back against a chair and thighs fully supported. They are instructed to lift the operated foot up, straighten the knee, and hold for a five-second count. They must not raise thigh off of the chair.
- **Heel Slides with Quad Sets**, participants are asked to lie down on their back with their not affected leg bent at the knee. They are instructed to tighten the thigh and buttocks of the affected leg

Table 1: Users' scoring the 10-point Likert scale usability questions (strongly disagree (1) to strongly agree (10)).

Questions \ Subject ID	1	2	3	4	5	6	7	8	9	10	Average
Did you enjoy your experience with the system?	9	9	9	8	9	9	9	8	7	9	8.6 ± 0.7
Were you successful using the system?	10	9	9	9	10	10	9	9	7	9	9.1 ± 0.88
Is the information provided by the system clear?	9	9	8	9	9	9	9	8	8	10	8.8 ± 0.63
Do you find the system easy to use?	9	8	9	8	9	9	8	9	7	9	8.5 ± 0.71
How easily did you learn to use the system?	9	9	8	8	10	9	8	8	8	9	8.6 ± 0.7
How accurate did you find the angle measurement?	9	8	8	9	10	9	9	9	8	8	8.7 ± 0.67
How accurate did you find the rep counts?	10	9	9	9	10	10	9	9	8	10	9.3 ± 0.67
Do you think that this system will be helpful for your rehabilitation?	10	9	9	9	10	10	9	9	9	9	9.3 ± 0.48
If prescribed by a healthcare practitioner, would you use the Recupe and perform the exercise program daily?	10	10	10	10	10	10	10	10	9	10	9.9 ± 0.32

and hold it for 5 seconds, then, bend their knee and pull the heel towards the buttocks for 3 seconds.

- **Toe Raises**, participants are asked to stand facing the kitchen sink with a firm hold on the kitchen sink. They are instructed to rise up on toes then back on heels and stand as straight as possible.
- **Reverse Toe Raises**, participants are asked to stand holding onto a chair or supportive object. They are instructed to raise their toes and feet off the floor, then, slowly lower toes back to the floor.
- **Ankle Pump**, participants are asked to place a pillow under the ankle, and lie flat on the floor. They are instructed to bend ankles to move feet up and down. They must not make use of a chair to do this exercise.
- **Seated Ankle Pump**, participants are asked to begin sitting upright with one leg straight forward. They are instructed to slowly pump their ankle by bending their foot up toward their body, then pointing their toes away from their body. They must make sure to move their foot in a straight line and try to keep the rest of their leg relaxed.

5 RESULTS AND DISCUSSION

The questionnaire that the subjects were asked to fill out after their experiment, is designed by our expert clinicians and engineers to evaluate the system usability and accuracy of exercises. The system usability questions along with the participants' 10-point Likert scale scores, where 1 strongly disagrees and 10 strongly agrees, are included in the Table 1. The average 10-point score given to each usability question is determined in the last column of this table. Each participant rated the exercises based on their experience, the average scores given by the participants to each of the exercises are visualized in Figure 4. The grey error bar located in the center of the exercise bar represents the standard deviation of exercise scores. The Users' average range of motion for each exercise that has been measured by the algorithm, is extracted from the database, and Figure 5 indicates the participants' average range of motion measured for each exercise. The grey error bar in the middle of each exercise bar identifies the standard deviation of participants' range of motion. Based on the records, the average user satisfaction of the platform is $93\% \pm 6.4$, and the average participants' score to the accuracy of the 6 exercises is $90\% \pm 4.6$.

6 CONCLUSION AND FUTURE WORK

In this paper, Plethy Recupe has been introduced to assist the patients through their musculoskeletal rehabilitation beyond the clinical environment. The system consists of a wearable sensor, a smartphone application, and a clinical dashboard that enables therapists to remotely set up specific rehabilitation programs de-

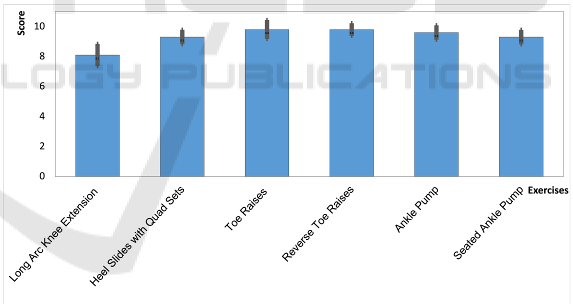

Figure 4: Average 10-point score given by participants to each of the 6 exercises.

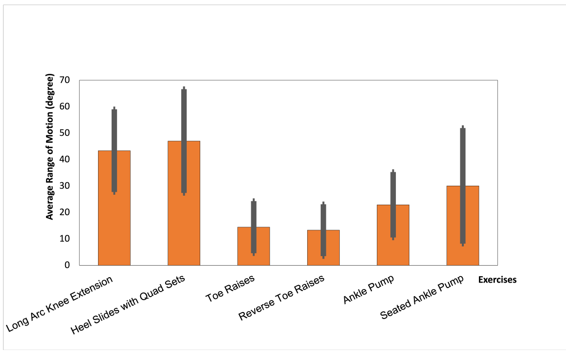

Figure 5: Average range of motion performed by participants for each of the 6 exercises.

pending on patient disorder and characteristics and to monitor patient progress over time. With the aid of accelerometer and gyroscope signals read by the single IMU in the sensor unit, we count the successful exercise repetitions and guide the user to correctly perform the exercises. We picked 6 pre-tested exercises from the library. These six exercises are under pilot study in the hospitals we collaborate with as well. The result of the study on 10 healthy subjects with the supervision of a team of expert clinicians proves 90% of the user satisfaction score for the exercises. The major limitation of this study is that the system evaluation and the evaluation results are conducted only on healthy subjects, however, our future prospective is to extensively evaluate the Plethy platform by musculoskeletal disorders patients.

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