

# Rehabilitation System for Limbs using IMUs

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## Abstract

In this work, we present an IMU-based rehabilitation system for upper and lower limbs. This system uses two wearable IMU sensors to detect rehabilitation motions of patients suffering from frozen shoulder, knee surgery, and hip surgery. The sensors are also connected to a smartphone via Bluetooth, and an Android APP is designed to show the correctness and the statistics of the rehabilitation exercises. The experimental results show that the average errors of knee angle, and elbow angle are both less than  $5^\circ$ . The average recognition rates of all the rehabilitation exercises are larger than 85%.

## I. INTRODUCTION

Population aging is a key issue in health for many countries. Frozen shoulder and joint degeneration are common diseases among elders. On the other hand, when people get injured on limbs, they usually cannot move the injured limbs for a period of time. As a result, the limbs become weaker and gradually lose their mobilities. Therefore, for patients who suffer from frozen shoulder, knee surgery, or limb surgery, they need to conduct rehabilitation exercises to restore the strength of the injured joints or limbs.

To kick off the rehabilitation exercises, first, physical therapists instruct the patients about the rehabilitation motions at the hospital. Then, the patients conduct the rehabilitation motions at home regularly. However, it is very likely that the patients neglect the correctness of the rehabilitation motions without any monitoring or guidance at home. Incorrect rehabilitation motions usually result in a slower process of recovery. Thus, if there is a system that can monitor the rehabilitation motions, judge the correctness, and report the exercise data to the physical therapists, the cost of rehabilitation, such as time duration, medical resources, and expenses can be reduced.

There are some camera-based rehabilitation systems publicly available [1] [2]. PAPAMAMA is a commercial rehabilitation system using cameras to monitor and judge the correctness of rehabilitation motions [1]. The system can also upload the rehabilitation data to the cloud for further evaluation. However, the system has a drawback that the patients have to perform rehabilitation exercises in front of

the cameras rather than anywhere else. On the other hand, the system is bulky and quite expensive as using cameras.

Another camera-based rehabilitation system is an APP using cameras from the smartphone [2]. The patient first adjusts the appropriate distance between the camera of the smartphone and himself/herself. When the APP detects the location of lower limbs of the patient, the patient can start to conduct the lower limb rehabilitation motions. The APP can also upload the rehabilitation data to cloud for evaluation or ranking. However, the system has a drawback that the patients still have to perform rehabilitation exercises in front of the camera rather than anywhere else. On the other hand, the system only focuses on the lower limb rehabilitation motions.

Therefore, it is desirable to develop a lightweight wearable rehabilitation system that is free of space constraint for patients. These were some studies about using Inertial Measurement Unit (IMU) to help people monitor their body movements instantaneously [3] [4] [5] [6] [7] [8] [9]. For example, a system that analyzed gait phase by a wearable device with two IMU sensors was proposed in [3]. The system also used the Euler angles from the IMU sensors to measure the stride count, and walking distance. The system can be used for gait assessment from a long-term knee angle monitoring. In [4], a single-sensor system was also proposed for measuring stride count, step height, and the distance of step trajectory.

Hence, in this work, we present an IMU-based rehabilitation system for upper and lower limbs. This system uses two wearable IMU sensors to detect rehabilitation motions of patients suffering from frozen shoulder, knee surgery, and hip surgery. The sensors are connected to a smartphone via Bluetooth, and an Android APP is designed to show the correctness, and statistics of the rehabilitation exercises. The experimental results demonstrate that the average errors of the knee angle, and elbow angle are less than  $5^\circ$ . The average recognition rates of all the rehabilitation exercises are larger than 85%. Furthermore, the important data such as the swing angles of the upper limbs, the knee joint angle, the thigh angle, and the abduction angle of lower limbs in the exercises are shown on the APP for reporting the current status of recovery.

## II. METHOD

We develop a rehabilitation system with two wearable Gyro sensors [10]. The Gyro sensor consists of 9-axis IMU, a microcontroller (TI CC264), a battery (3.7V, 85mAh), and a Micro USB connector for charging. To reduce the angle

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drift in the integration of angular velocity for having Euler angles, Gyro sensor has a calibration mechanism that refers to magnetic north.

#### A. Rehabilitation exercises for the upper limbs

To detect the rehabilitation motions about the upper limbs, we wear an elbow guard as shown in Fig. 1, where the two sensors are attached to the upper arm, and forearm. The Roll, Yaw, and Pitch angles are defined as being rotated by X-axis, Y-axis, and Z-axis, respectively. For the wearable device setting in Fig. 1, the Roll angle and Pitch angle of both sensors are  $90^\circ$  and  $0^\circ$ , respectively. The rehabilitation motions for frozen shoulder are summarized in Fig. 2.

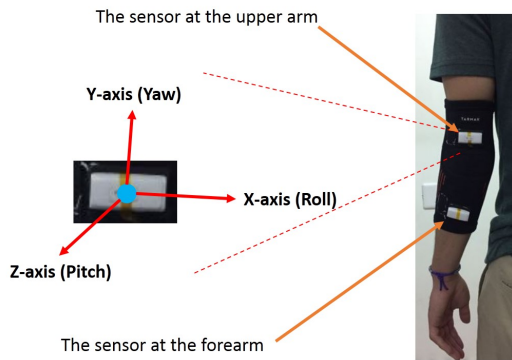


Fig. 1 The wearable device setting at the upper limb.

The conditions for recognizing these rehabilitation motions are also summarized in TABLE I, where Roll angle, Pitch angle, and X-axis, Z-axis Angular Velocities (A.V.) are used to detect the correctness of different motions. For the climbing motions with the left hand, the patient first conducts the motion to reach a point as high as he/she can in the air for both front climbing and side climbing, where the Roll angle is a negative value. The Roll angle at the upper arm at this point is set as the setting value. Thus, when the Roll angle is smaller than the setting value (the minimum Roll angle in the climbing exercise is  $-90^\circ$ ), the climbing motions are recognized.

Similarly, before the patient performs the pendular exercises, the system records the current Roll angle and Pitch angle from the data source sensor as the setting values. Thus, when the Roll angle and Pitch angle satisfy the requirement in the corresponding motions in TABLE I, the pendular exercises are recognized. For the pendular exercise (front-back), X-axis Angular Velocity  $< -200$  and Roll angle  $< S-30$  are conditions for the front swing of the exercise. X-axis A.V.  $> 200$  and Roll angle  $> S+30$  are conditions for the back swing of the exercise. The order of these conditions in the front swing and back swing is irrelevant to the recognition. In the pendular exercise (left-right), note that the back of hand of the patient has to face forward at the initial location (Fig. 6(b)) for the correct swing angle calculation and judgement. Then we use the forearm sensor to judge this exercise. For this exercise, X-axis A.V.  $> 200$  and Roll angle  $> S+30$  are conditions

for the left swing of the exercise. X-axis A.V.  $< -200$  and Roll angle  $> S-30$  are conditions for the right swing of the exercise. For the pendular exercise (circumduction), when the patient performs the exercise satisfying the Roll angle and Pitch angle conditions, the exercise is recognized.

The pulling towel exercise, however, uses two sensors to calculate the elbow joint angle for the judgement. In Fig. 3, the sensor at the upper arm measures  $a^\circ$  in related to the vertical line from its Roll angle and the sensor at the forearm measures  $-b^\circ$  in related to the vertical line from its Roll angle.  $(a - (-b))$  is exactly the elbow joint angle. When the patients are ready to conduct the pulling towel exercise as shown in the left of Fig. 2(f), the system records the Roll and Pitch angles from the sensor at the forearm as the setting values for the pulling towel exercise.

Note that for each rehabilitation motion, in addition to the correctness judgement, the swing angle will be calculated during the exercise indicating the status of recovery. These mentioned setting values will be used to calculate the swing angle in the climbing exercises and pendular exercises.

We use the Roll angle from the upper arm sensor to calculate the swing angle for the climbing exercises and pendular exercise (front-back). The swing angles in the climbing exercises are shown in Fig. 4(a) and Fig. 4(b). The swing angles are the blue arcs in Fig. 5.

Similarly, we use the Roll angle from the forearm sensor to calculate the swing angle for the pendular exercise (left-right) since the swing is around X-axis. The swing angles are the blue arcs in Fig. 6, which are calculated by the difference of Roll angles at the target location and initial location.

The system also calculates the maximal oval area of pendular exercise (circumduction). We set the arm length as 40 centimeters, and use the equation  $(\sin(\text{maximumRoll}) \cdot \text{armlength}) \cdot (\sin(\text{maximumPitch}) \cdot \text{armlength}) \cdot \pi$  to get the maximum oval area approximately. If this area is increased, the status of recovery for the patient is better. The detailed illustration for calculating this area is shown in Fig. 7.

#### B. Rehabilitation motions for the lower limbs

For the rehabilitation of lower limbs, we wear a kneepad equipped with two sensors at the thigh and calf as shown in Fig. 8. In this device setting, the Roll angle and Pitch angle of both sensors are  $-90^\circ$  and  $0^\circ$ , respectively. The rehabilitation motions for lower limbs are summarized in Fig. 9. The conditions for recognizing these rehabilitation motions are summarized in TABLE II as well, where thigh, knee, and abduction angles are used to detect the correctness of these motions.

In Fig. 10, the sensor at the thigh measures  $a^\circ$  in related to the horizontal line from its Roll angle as the thigh angle and the sensor at the calf measures  $-b^\circ$  in related to the horizontal line from its Roll angle. Hence,  $(a - (-b))$  is exactly the knee angle. When the patient performs the knee-to-chest exercise without help of hands, the system records the knee and thigh

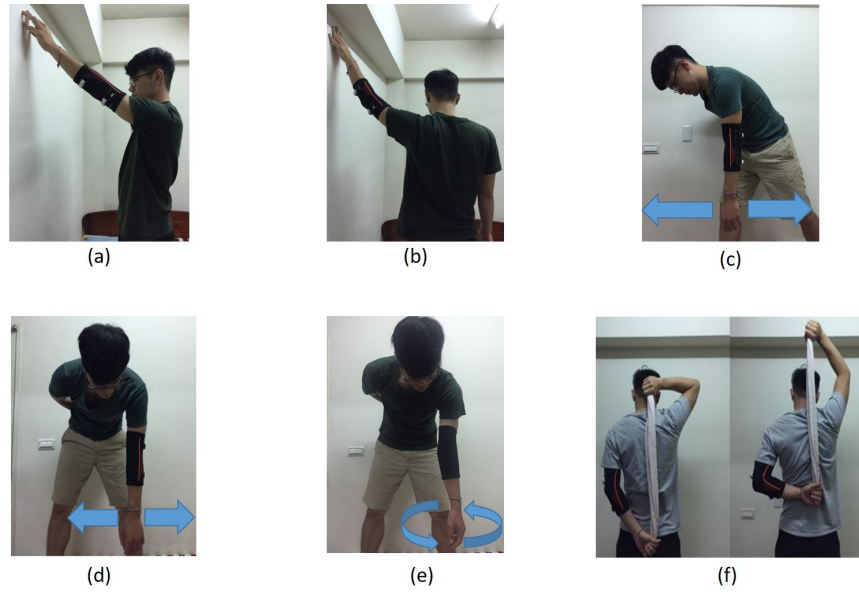
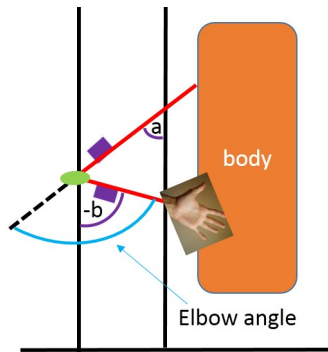


Fig. 2 The rehabilitation motions for the frozen shoulder. (a) Climbing exercise (front). (b) Climbing exercise (side). (c) Pendular exercise (front-back). (d) Pendular exercise (left-right). (e) Pendular exercise (circumduction). (f) Pulling towel exercise.

TABLE I: The conditions for judging the upper limb rehabilitation motions. “S” represents the Setting value. “A.V.” represents Angular Velocity. “P” represents current Pitch angle.

	Climbing Exercise		Pendular Exercise			Pulling towel
	Front	Side	Front-Back	Left-Right	Circumduction	
Data source	upper arm	upper arm	upper arm	forearm	upper arm	fore+upper arms
Roll angle ( $^{\circ}$ )	$<S$	$<S$	$<S-30; >S+30$	$>S+30; <S-30$	$<S-10; >S+10$	$<S$
Pitch angle ( $^{\circ}$ )	-	-	-	-	$<S-10; >S+10$	$S-10 < P < S+10$
X-axis A.V. ( $^{\circ}/s$ )	$>60$	-	$<-200; >200$	$>200; <-200$	-	-
Z-axis A.V. ( $^{\circ}/s$ )	-	$>60$	-	-	-	-
Elbow angle ( $^{\circ}$ )	-	-	-	-	-	$>80$



$$\text{Elbow angle} = a - (-b) = a + b$$

Fig. 3 The elbow angle calculation.

angles as the setting values. After that, once the thigh and knee angles satisfy the requirement in TABLE II, the knee-to-chest exercise is recognized, either with hands or without hands.

In Fig. 11, the sensor at the thigh measures  $a^{\circ}$  in related

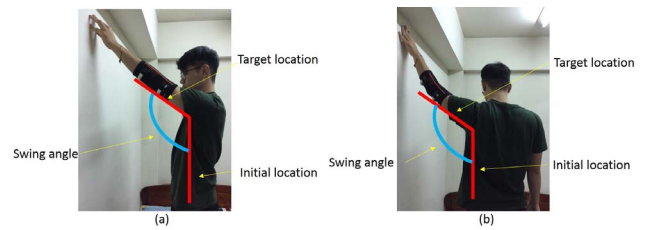


Fig. 4 (a) The climbing exercise (front). (b) The climbing exercise (side).

to the vertical lines from its Yaw angle as the abduction angle. Similarly, when the patient performs the hip-abduction exercise without any help, the system records the abduction angle as the setting value. After that, once the abduction angle satisfies the requirement in TABLE II, the hip-abduction exercise is recognized, either with or without others' help.

### C. User-defined rehabilitation motions

The patient can set any specific motion he/she desires with the elbow guard on the elbow or the kneepad on the knee in our system. When the patient keeps his/her limbs intact

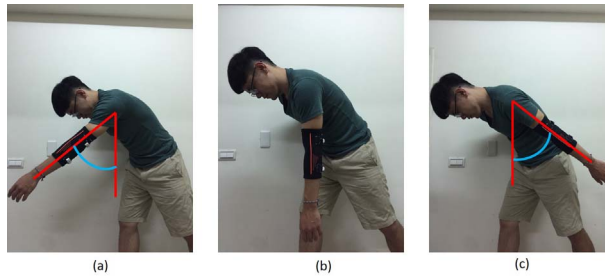


Fig. 5 The pendular exercise (front-back). (a) Target location (front). (b) Initial location. (c) Target location (back).

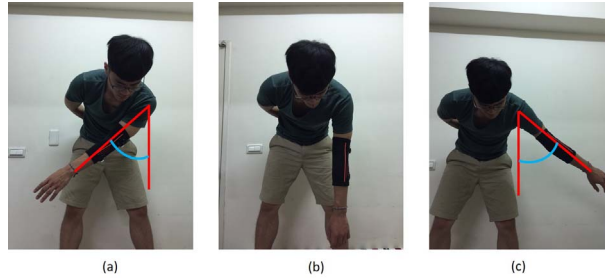


Fig. 6 The pendular exercise (left-right). (a) Target location (right). (b) Initial location. (c) Target location (left).

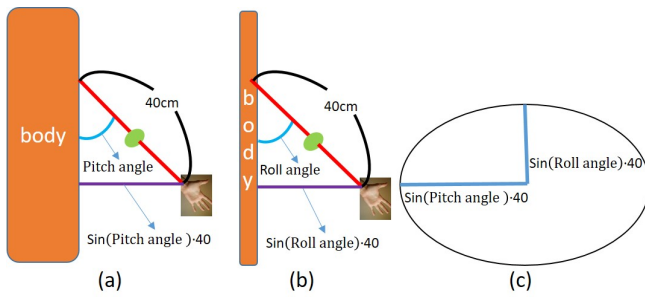


Fig. 7 (a) Left swing. (front view) (b) Front swing. (left view) (c) Oval area.

TABLE II: The conditions for judging the lower limb rehabilitation motions. “S” represents the Setting value.

	Knee-to-chest thigh, calf	Hip-abduction thigh
Data source	thigh, calf	thigh
Thigh angle (°)	>S	-
Knee angle (°)	>S	-
Abduction angle (°)	-	>S

for a few seconds, the system records the Roll and Pitch angles of the motion from the two sensors at either the elbow guard or kneepad as the setting value for the judgement. When the patient performs a rehabilitation exercise that satisfies the setting values, the exercise is recognized and its duration is displayed on the APP. The APP can also save these current user-defined rehabilitation exercises for further evaluation.

### III. ANDROID APPLICATION

The APP supports the upper limb rehabilitation exercise, lower limb rehabilitation exercise, and user-defined rehabilita-

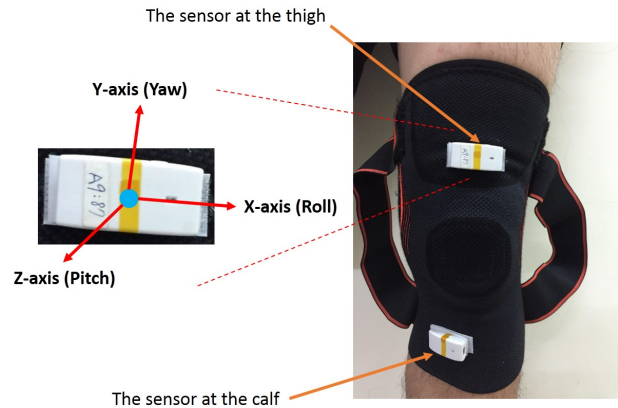


Fig. 8 The wearable device setting at the lower limb.

tion exercise, and provides rehabilitation data statistics.

#### A. The upper limb rehabilitation exercise page

In Fig. 12(a), the page shows the maximum swing angles for the climbing exercises (front, and side), swing angles for the pendular exercises (left, right, front, and back), oval area for the pendular exercise (circumduction), and the progress of the rehabilitation exercises for seconds or times in real time on the leftmost column. The current rehabilitation motion image on the middle column. The control buttons of this page include the Next, Reset, Start, Calibration (CAL.), and Finish buttons on the rightmost column. The Next button can change to the next motion when the patient wants to conduct the next rehabilitation motion. The Reset button initializes all recorded values on the APP’s GUI. The Start button starts the detecting motion and rehabilitation time calculation. The CAL. button



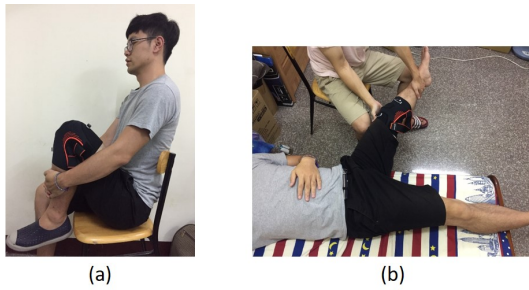


Fig. 9 The rehabilitation motions of the lower limbs. (a) Knee-to-chest exercise. (b) Hip-abduction exercise.

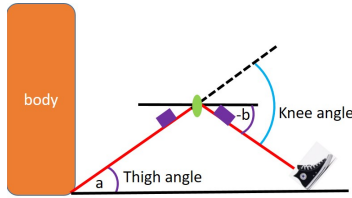


Fig. 10 The thigh and knee angles calculation.

records the initial Roll and Pitch angles for detecting the pendular exercises and calculation the swing angles (front, back, left, and right). The Finish button means ending the rehabilitation exercises and saving important data as the excel file in the smartphone, where the important data includes the rehabilitation time, rehabilitation date, maximum swing angles, and maximum oval area. The setting value buttons include a Climb angle setting button for the climbing exercises, Towel angle setting button for the pulling towel exercise on the second to last row.

#### B. The lower limb rehabilitation exercise page

For Fig. 12(b), the page shows the maximum knee, thigh, and abduction angles and the progress of the rehabilitation exercises for the seconds in real time on the leftmost column. The image of the current rehabilitation exercise on the middle column. The control buttons of the page include the Next, Reset, Start, and Finish buttons on the rightmost column. The Next, Reset, Start buttons have the functions the same as the upper limb rehabilitation exercise page. The Finish button means ending the rehabilitation exercises and saving important data as the excel file in the smartphone, where the important data includes the rehabilitation time, rehabilitation date, maximum thigh, knee and abduction angles. The setting value buttons include a Hip-abduction setting button for the hip-abduction exercise, and a Knee-to-chest angle setting button for the knee-to-chest exercise on the second to last row.

#### C. The user-defined rehabilitation exercise page

For Fig. 13, each name corresponds to a rehabilitation exercise and the progress of the rehabilitation exercise for the seconds in real time on the leftmost column. The Enter name

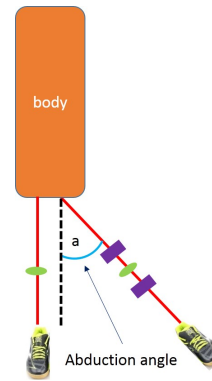


Fig. 11 The abduction angle calculation.

button can input the entered name to the name lattice of the leftmost column. The record buttons (REC) on the rightmost column can record the Roll and Pitch angles from the two sensors at elbow guard or kneepad for the judgment. The Save configuration and Load configuration buttons are on the second to last row for saving and loading the configurations.

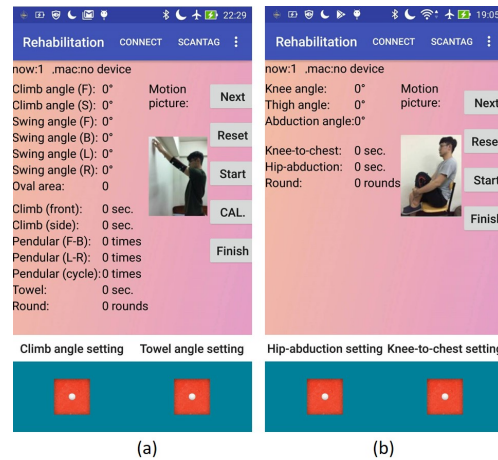


Fig. 12 The Graphical User Interface (GUI) of APP. (a) The upper limb rehabilitation exercise page. (b) The lower limb rehabilitation exercise page.

#### D. The data statistics page

For this page, the important data is recorded as an excel file in the smartphone, and then the APP uses the data to create a line chart that clearly shows the degree of recovery. The patient can select a kind of important data to make the line chart in the APP. The complete process is shown in Fig. 14.

### IV. EXPERIMENTAL RESULTS

In this section, we present the recognition rate of all rehabilitation exercises, the accuracy of the knee angle and elbow angle. The measurement results are summarized in TABLE III. In this study, 10 healthy volunteers (10 males) between 23 and 60 years old. The heights of the volunteers are between 160 and 178 centimeters, and the weight of the volunteers are between 62 and 80 kilograms.

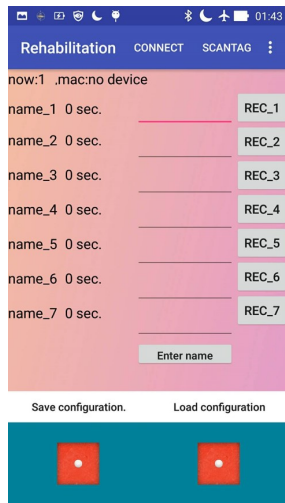


Fig. 13 The user-defined rehabilitation motion page.

The participants were asked to conduct all rehabilitation motions for 100 times with the elbow guard on the left elbow and the kneepad on the left knee.

#### A. Recognition rate in upper rehabilitation motions

The experimental results are shown in Columns 2 to 7 of TABLE III. According to TABLE III, the average recognition rates of the climbing exercises and pulling towel exercise are 100%. The average recognition rates of the pendular exercises are lower than 100% because the participants sometimes swing too small angle such that the exercises cannot be detected. Hence, the error is reasonable.

#### B. Recognition rate in lower rehabilitation motions

The experimental results are shown in Columns 8 to 9 of TABLE III. According to TABLE III, the average of knee-to-chest, and hip-abduction exercises are 100%. Before the participants conduct the motions, we have to record the setting values to help the exercise detection. Hence, the results are expected.

#### C. Elbow angle calculation

The experimental results are shown in Column 10 of TABLE III. We measured the elbow angle then average from the pulling towel exercise for 10 times. The test data is measured from the wearable device. The ground truth data are measured from a joint protractor. We calculated the average error as the results for the participants. According to TABLE III, the average of absolute mean error in elbow angle is  $4.6^\circ$ .

#### D. Knee angle calculation

The experimental results are shown in Column 11 of TABLE III. We measured the knee angle then average from the knee-to-chest exercise for 10 times. The test data is measured from the wearable device. The ground truth data are also measured from a joint protractor. We calculated the average

error as the results for the participants. According to TABLE III, the average of absolute mean error in knee angle is  $4.5^\circ$ .

## V. CONCLUSIONS

This paper presents a lightweight rehabilitation system with two IMU sensors. The rehabilitation system can be used for long-term rehabilitation motion recognition at home. The Android APP records the important data in the smartphone. Then the patients can use the data to understand the recovery status of the affected limbs. These data can also help physical therapists to understand patient's recovery process. The experimental results demonstrate that the absolute mean error in knee angle and elbow angle are less than  $5^\circ$ . The average recognition rates of all the rehabilitation motions are higher than 85% indicating the effectiveness of system.

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1	Date	Rehabilitation time (minute:second)	Climb angle (front)	Climb angle (side)	Swing angle (front)	Swing angle (back)	Swing angle (left)	Swing angle (right)	Oval area
2	2019-03-19 04:02:52	1:5	163	161	85	36	47	48	5235
3	2019-03-19 04:29:56	1:10	171	156	89	41	45	60	5167
4	2019-03-19 04:31:07	1:7	165	156	88	34	47	55	4875

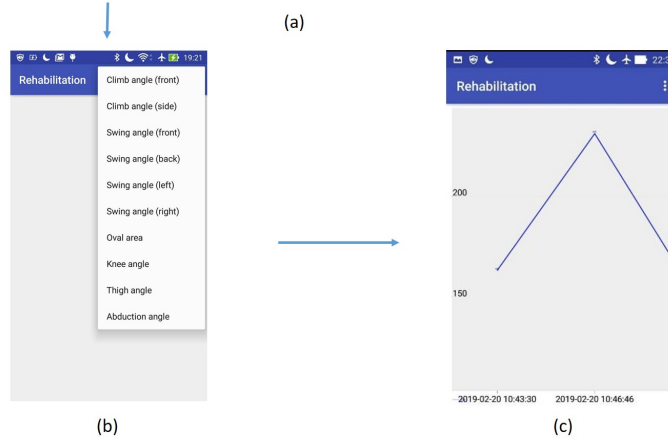


Fig. 14 The process of the data statistics page. (a) Excel file. (b) Selection list. (c) Line chart, the horizontal-axis represents the date, and time, the vertical-axis represents the data value.

TABLE III: Experimental results.

Participant	Rehabilitation motions								Joint angle	
	Climbing (front) (%)	Climbing (side) (%)	Pendular (front-back) (%)	Pendular (left-right) (%)	Pendular (circum-duction) (%)	Pulling towel (%)	Knee-to-chest (%)	Hip-abduction (%)	Absolute Mean Error in Elbow angle (°)	Absolute Mean Error in Knee angle (°)
1	100	100	98	99	89	100	100	100	4.6	2.6
2	100	100	96	95	85	100	100	100	3.2	3.4
3	100	100	100	97	82	100	100	100	5.0	5.8
4	100	100	100	98	86	100	100	100	3.0	3.6
5	100	100	95	96	83	100	100	100	3.4	5.2
6	100	100	100	97	84	100	100	100	4.8	4.4
7	100	100	100	98	87	100	100	100	6.2	5.2
8	100	100	100	98	88	100	100	100	2.6	4.8
9	100	100	97	98	84	100	100	100	7.2	5.8
10	100	100	100	98	82	100	100	100	6.8	4.4
Average	100	100	98.6	97.3	85	100	100	100	4.6	4.5