An IMU-aided Fitness System

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***Abstract*—In this work, we present an IMU-aided fitness system for users conducting exercises. The system utilizes the wearable 9-axis IMU sensors to detect three kinds of exercises including squat, bridge exercise, and double leg raise. The sensors are also connected to a smartphone via Bluetooth, and an Android APP is designed for users. The system can instantaneously report the correctness of exercises, show the statistics of workouts, and record the data in the cloud for references.**

I. Introduction

Nowadays, people's lifestyles are increasingly sedentary, which result in the rise of lifestyle-related illnesses. To prevent from being unhealthy, a great number of people hit gyms to keep their bodies in good condition. For most of people who are not professional in fitness, there are many ways to learn about the exercises of fitness, including hiring a fitness coach, or asking veterans. However, some beginners may still get hurt during their workouts when they conduct fitness alone or careless. Therefore, it is important to have a fitness system with APP to guide people correctly during exercises.

Among the exercises for fitness, the squat is a common and more challenging one. The squat is a functional exercise that trains your muscles for daily tasks, such as rising from chairs or picking up objects from a lower position. There are other benefits for squatting, including building muscles, burning calories, and strengthening lungs and hearts. However, when people conduct squats improperly, they may have physical injuries, like knee pains or lower back pains. In addition to squats, core exercises are also common and important for fitness. This is because core muscles are involved in most motions on the playing fields and in daily activities. Likewise, it may also lead to physical injuries when conducting these motions improperly.

There are some commercial APPs designed for fitness that are available in APP Stores [9] [11] [12]. Fitbod is an APP that fuses the data of users' strength-training ability, previous workouts, and the available equipment to help build personalized workout menus [9]. It provides the instructions and videos to show users the correct motions. Nike Training Club is an APP that helps people reach their fitness goals with some designed workouts [11]. It provides programs that are flexible for all the users and videos to show them the correct motions. However, both the APPs have a common drawback that they are unable to correct the users' motions instantaneously. As a result, the users may conduct the motions incorrectly for a long period of time and cause injury.

Another fitness APP, Personal Trainer, is a system that utilizes the camera from a smartphone to track 16 key points on the users' bodies for judging the correctness of the motions [12]. Its operation flow is as follows. First, the users place their smartphones upright on a table or against a wall. Then, the users step back approximately 7 feet until the entire body is shown on the screen. When the users start to exercise, the system contrasts their poses with the ideal pre-defined poses. Furthermore, the system offers real-time audio feedback and video instructions to encourage the users to achieve the standard motions. Although the system instantaneously provides the function to correct the users' incorrect motions, it has some drawbacks as well. First, the system requires the users to conduct exercises in front of the camera rather than anywhere else. Second, the system may misjudge the correctness of the users' motions under some circumstances such as little space, insufficient light, or improper angle of the shot.

To avoid those mentioned drawbacks, we propose to leverage the low-cost Inertial Measurement Unit (IMU) sensors to develop a system that can monitor and guide the users' motions as well as be free of space and equipment constraints. In fact, there have been some studies about using the data collected by IMU sensors in movement analysis and motion recognition [1] [2] [3] [4] [5] [6] [7] [8].

For example, there are some studies about the gait analysis with the aid of IMU sensors. In [4], a system with a single IMU sensor was proposed for measuring stair count, step height, and the distance of step trajectory about lower limb exercises. In [7], a system was proposed to recognize 10 different scenarios of walking workouts based on a foot-mounted IMU sensor. In [8], a system with two IMU sensors was proposed for calculating the knee angle, stride count, and walking distance.

Furthermore, there are some studies about the analysis and recognition of rehabilitation exercises with the aid of IMU sensors. In [1], an algorithm was proposed to utilize the data of IMU sensor to compare the acquired motion patterns with sample patterns for evaluating the quality of rehabilitation exercises. In [3], a system with four IMU sensors was proposed for recognizing the rehabilitation motions of limbs.

More related to our work, there are some studies about the

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analysis and recognition of fitness exercises with the aid of IMU sensors. In [2] and [6], the studies were proposed to classify and calculate repetitions of multiple weight training and calisthenics exercises with the data from IMU sensor by machine learning techniques. In [5], a study was proposed to track and analyze the weight training exercises based on a dumbbell-mounted IMU sensor by signal and data processing techniques. The common drawback among these studies [2] [5] [6] is that they only recognize the motion but not judge its correctness. That is, even when the motion has been recognized successfully, the systems do not tell whether the motion is a standard one or just a similar but improper one. In fact, there may only be a slight difference between a standard motion and an improper one, but both the motions are recognizable. Thus, it is likely to get physical injuries when conducting improper motions repeatedly.

In this work, the proposed system utilizes at most three wearable 9-axis IMU sensors to detect three kinds of exercises including squat, bridge exercise, and double leg raise. Each exercise requires different amounts of sensors to satisfy the desired functions. The sensors are also connected to a smartphone via Bluetooth, and an Android APP is designed for users. The system can instantaneously report the correctness of exercises, show the statistics of workouts, and record the data in the cloud for references.

II. IMU Sensor

Our IMU-aided fitness system consists of three wearable 9-axis IMU sensors, which are designed and developed by GYRO SYSTEMS, INC [10]. The sensor contains a microcontroller (TI CC2640), 3-axis accelerometer, 3-axis gyroscope, 3-axis magnetometer (BOSCH BMI160), 85mAH 3.7V lithium-ion battery, Bluetooth 4.1, and a Micro USB connector for charging. The dimension and weight of the sensor are 38mm x 18mm x 11mm and 5g, respectively. The sampling rate of the sensor is 50Hz, and the error of Euler angles is less than 0.5° in static and less than 2° in dynamic.

The Roll, Pitch, and Yaw angles are defined as being rotated by X-axis, Y-axis, and Z-axis, respectively. For the 9-axis IMU sensor setting in Figure 1(a) (the black rectangle with round corners represents the IMU sensor, and the inner rectangle represents the power light of the sensor), the Roll angle and Pitch angle of the sensor are 90° and 0°, respectively. When the sensor is rotated by the X-axis in the direction shown as the red (forward) or yellow (backward) arrows in Figure 1(a), the Roll angle increases from 90° to 180° or decreases from 90° to 0°, respectively. The value of Roll angle is changed from 0° to 180° and from -0° to -180° as shown in Figure 1(b).

III. Method

A. Squat with barbells

At first, we tie a hook and a loop fastener on our right hand and wear a knee pad on the right foot as shown in Figure 2, where three 9-axis IMU sensors are attached to the wrist, thigh (above the knee), and shank (below the knee), respectively. The sensor on the wrist is right under the palm. The sensor on the thigh is approximately 9 centimeters above the knee. The sensor on the shank is approximately 8 centimeters below the knee. The Roll angles of the sensors in Figure 2 are 90° since they are vertical to the ground. The Roll angles will increase (decrease) when the sensors rotate forward (backward). The system can detect three situations in a squat exercise including *good morning*, *hip joint deactivation*, and *completeness*. The first two are about the detection of incorrect motions, and the last one is about the recognition of a complete squat.

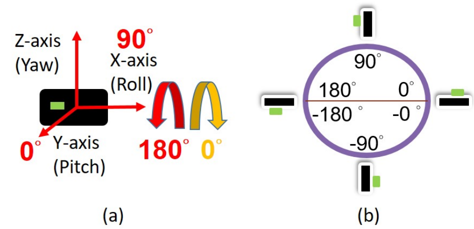

Fig. 1: The setting of the 9-axis IMU sensor. (a) The demonstration of Euler angle of the sensor. (b) The demonstration of positive and negative intervals of the Roll angle of the sensor.

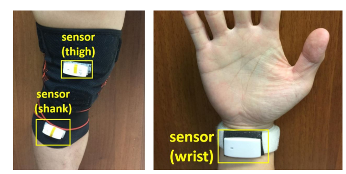

Fig. 2: The wearable devices on wrist and knee.

Prior to the exercise, the system requires three motions for calibration as shown in Figure 3, including stand, pre-squat, and squat without holding barbells. For the posture of stand, the users stand as feet together without leaning forward or backward. The system then records the Roll angle (C1) of the sensor on the thigh. For the posture of pre-squat, the users conduct a quarter squat, which is used to set up a threshold for rising in a complete squat. The system then records the Roll angle (C2) of the sensor on the thigh. For the posture of squat without holding barbells, the users squat with the activation of hip joint. The system then records the Roll angle (C3) of the sensor on the shank.

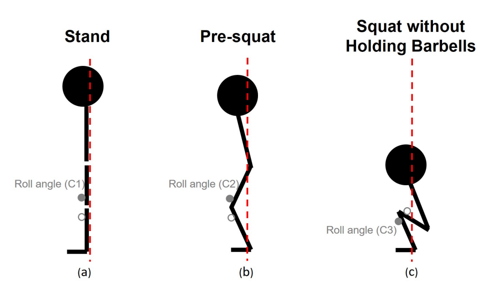

Fig. 3: Three calibration motions for squat. (a) The posture of stand. (b) The posture of pre-squat. (c) The posture of squat without holding barbells.

When conducting the squat, the users try to keep the barbell moving on the trajectory of the straight red dotted line in Figure 4. The good morning squat occurs when the users bend the body during the process of squat, where the barbell moves forward such that it is out of the trajectory of red dotted line. The good morning squat occurs in two scenarios, one is bending the body when squatting (Figure 4(c)), the other is bending the body when rising (Figure 5(b)). Next, let us explain how to detect the good morning squat. Since the wrist equips with a sensor and the users always hold the barbell tight, the Roll angle of the sensor on the wrist should be invariant during the squat. When the Roll angle of the sensor on the thigh is equal to C2 (pre-squat), the system records the Roll angle of the sensor on the wrist as the setting value (S). Then we use the X-axis angular velocity (A.V.) of the sensor on the thigh for detecting squatting or rising. Specifically, when the X-axis A.V. of the sensor on the thigh is less than -10 or greater than 10, the squatting or rising occurs, respectively. Thus, when the Roll angle of the sensor on the wrist is greater than S+10 under squatting or rising, that means the body is bending, the good morning squat occurs and is detected.

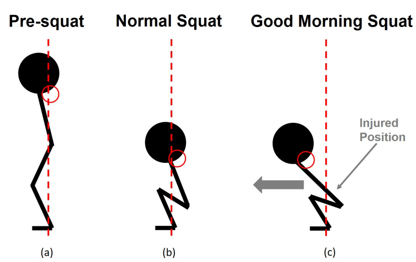

Fig. 4: Good morning squat demonstration (down). (a) Posture of pre-squat. (b) Posture of normal squat. (c) Posture of good morning squat and the injured position.

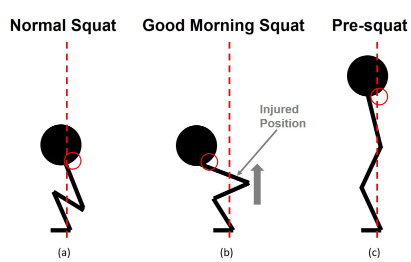

Fig. 5: Good morning squat demonstration (up). (a) Posture of normal squat. (b) Posture of good morning squat and the injured position. (c) Posture of pre-squat.

Regarding the hip joint deactivation detection, we observed that when conducting the squat correctly, the users should squat like sitting on a chair as shown in Figure 6(a) rather than sitting on the top of their heels as shown in Figure 6(b). To detect the hip joint deactivation, we set the following conditions. If the Roll angle of the sensor on the thigh is less than C1-90 and that on the shank is greater than C3+5, the hip joint is judged as been deactivated.

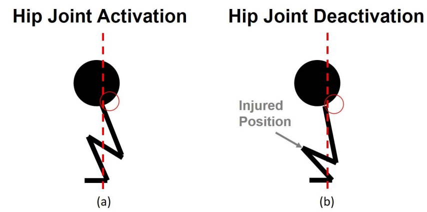

Fig. 6: Hip joint deactivation demonstration. (a) Posture of hip joint activation. (b) Posture of hip joint deactivation.

Regarding the completeness, if the hip joint first reaches the same level of knee joint and then exceeds the level of hip joint during pre-squat, a complete squat is recognized. Thus, we set that the Roll angle of the sensor on the thigh is less than C1-90 and is greater than C2 as the conditions for detecting the completeness of a squat.

The conditions of the related sensors for good morning squat detection, hip joint deactivation detection, and completeness detection are summarized in TABLE I. If users do not receive both the warnings of good morning squat and hip joint deactivation when conducting a squat, the motion is recognized as a correct squat; otherwise, it is an incorrect motion.

B. *Bridge exercise*

At first, we tie a hook and a loop fastener on the chest and wear a waist support as shown in Figure 7, where the two 9-axis IMU sensors are attached to the chest and waist, respectively. Both the sensors on the chest and waist are in the middle of the upper body. The Roll angles of both sensors in Figure 7 are 90° again. The Roll angles will increase (decrease) when the sensors rotate forward (backward). The system can detect two situations in a bridge exercise including *non-neutral spine* and *completeness*. These two are about the detection of incorrect motions and the recognition of a complete bridge exercise, respectively.

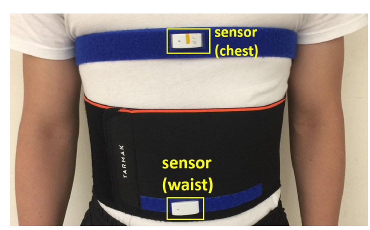

Fig. 7: The wearable devices on the chest and waist.

Prior to the exercise, the system requires two motions for calibration as shown in Figure 8, including flat back and bridge. For the posture of flat back, the users flat their backs to the ground. The system then records the Roll angle (C1) of the sensor on the waist. For the posture of bridge, the users conduct the motions of bridge exercise, which rises from the posture of flat back to the posture of bridge by using the strength of hip. The system then records the Roll angles (C2 and C3) of both sensors on the chest and waist. Additionally, the movement

	Good Morning				*Hip Joint Deactivation*		*Completeness*
	Down		*Up*				
Data source	thigh	wrist	thigh	wrist	thigh	shank	thigh
Roll angle (°)	-	>S+10	-	>S+10	<C1-90	>C3+5	<C1-90; >C2
X-axis A.V. (°/s)	<-10	-	>10	-	-	-	-

TABLE I: The conditions for detecting squats. "S" represents the Setting value. "A.V." represents Angular Velocity.

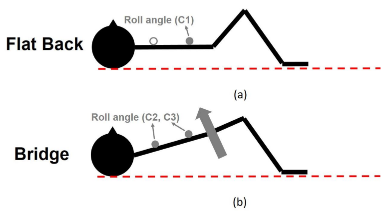

Fig. 8: Two calibration motions for bridge exercise. (a) Posture of flat back. (b) Posture of bridge.

angle of bridge exercise, which is the difference between C1 and C3, is calculated during the calibration.

When conducting the bridge exercise, the users should conduct the motions with the strength of hip instead of lower back such that the spine will be in a neutral state (Figure 9(a)). Otherwise, the spine may be in a non-neutral state and the chest may rise (Figure 9(b)). Thus, we can detect the occurrence of non-neutral spine by the sensors on the waist and chest as follows. If the bridge exercise is recognized (explained in the next paragraph) and the Roll angle of sensor on the chest is less than C2-10, the state of the non-neutral spine occurs.

Regarding the completeness, we use the sensor on the waist for the detection and set the following conditions. If the Roll angle of the sensor on the waist is less than C3+5, the bridge exercise is recognized. Furthermore, we allow users to set the duration (T) of the bridge exercise. If users conduct a bridge exercise for T seconds, they complete a bridge exercise.

The conditions about the readings on the related sensors for non-neutral spine detection and completeness detection are summarized in TABLE II. If users do not receive the warning of non-neutral spine when conducting a bridge exercise, the motion is recognized as a correct bridge exercise; otherwise, it is an incorrect motion.

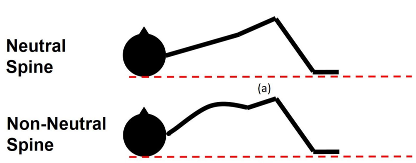

Fig. 9: The demonstration of the posture of neutral spine and non-neutral spine for bridge exercise. (a) The posture of neutral spine. (b) The posture of non-neutral spine.

C. Double leg raise

At first, we wear a knee pad on our right foot and a waist support as shown in Figure 10, where two 9-axis IMU

	Non-neutral Spine		*Completeness*
Data source	waist	chest	waist
Roll angle (°)	<C3+5	<C2-10	<C3+5

TABLE II: The conditions for detecting bridge exercises.

sensors are attached to the thigh (above the knee) and lower back, respectively. The sensor on the thigh is approximately 9 centimeters above the knee. The sensor on the lower back is in the middle of the upper body. The Roll angles of the sensors on the thigh and lower back are 90° and 270° as shown in Figure 10, respectively, since they are both vertical to the ground. The Roll angles will increase (decrease) when the sensors rotate forward (backward). The system can detect two situations in a double leg raise including *non-neutral spine* and *completeness*. These two are about the detection of incorrect motions and recognition of a complete double leg raise, respectively.

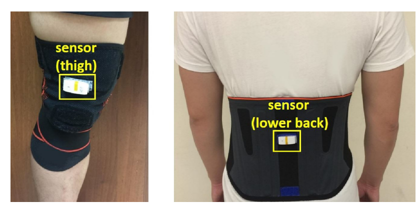

Fig. 10: The wearable devices on knee and lower back.

Prior to the exercise, the system requires three motions for calibration as shown in Figure 11, including raise, drop, and flat back. For the posture of raise, the users raise their feet to a high level they want, but not reach to the vertical level. This level is the level that users must exceed when conducting the raise motion every time. The system then records the Roll angle (C1) of the sensor on the thigh. Note that C1 is 270° when the legs are raised to the vertical level. For the posture of drop, the users drop their feet to a low level they want, but not reach to the ground level, which means that users have to drop their feet lower than this level when conducting the drop motion every time. The system then records the Roll angle (C2) of the sensor on the thigh. Note that C2 is greater than C1. For the posture of flat back, the users flat their backs to the ground. The system then records the Roll angle (C3) of the sensor on the lower back. Additionally, the swing angle of legs, which is the difference between C1 and C2, is calculated during the calibration.

When conducting the double leg raise, the users should keep their lower backs flat to the ground. Otherwise, the spine may be in a non-neutral state. Thus, we use the sensor on the lower back to detect the occurrence of non-neutral spine as follows. If the Roll angle of the sensor on the lower back is greater than

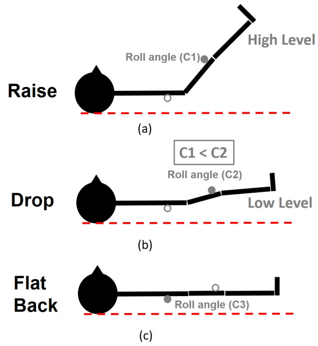

Fig. 11: Three calibration motions for double leg raise. (a) Posture of raise. (b) Posture of drop. (c) Posture of flat back.

	Non-neutral Spine		*Completeness*
Data source	thigh	lower back	thigh
Roll angle (°)	[C1,C2]	>C3+2; <C3-2	<C1; >C2

TABLE III: The conditions for detecting double leg raises.

C3+2 or less than C3-2 when conducting double leg raise, the state of the non-neutral spine occurs.

Regarding the completeness, we use the sensor on the thigh to detect the motion based on the following conditions. If the Roll angle of the sensor on the thigh is less than C1 (legs are higher than the high level) and is greater than C2 (legs are lower than the low level), a double leg raise is recognized.

The conditions of the related sensors for non-neutral spine detection and completeness detection are summarized in TABLE III. If users do not receive the warning of non-neutral spine when conducting a double leg raise, the motion is recognized as a correct double leg raise; otherwise, it is an incorrect motion.

IV. Android Application

In this section, we introduce the functionalities of the designed APP including the main pages of three exercises, the statistics of workouts, and the real-time haptic and audio feedback.

A. The APP page for squat

In Figure 12, the page shows the counters of correct and wrong motions, group, and the weight of the barbell in the middle. The dark blue control buttons on the right side of the page include the Start, Group Finish, Calibration (CAL.), Weight, History, Statistics, Upload, and End buttons. The Start button activates the detections of the squat. The Group Finish button terminates the detection and records the count as a group. The CAL. button records the Roll angle when users conduct the three calibration motions as shown in Figure 3. The Weight button records the weight of barbell. The History button shows the important records such as finish time, group count, maximal holding weight of barbell, and the counts for good morning squat (down), good morning squat (up), hip joint deactivation, and completeness. The Statistics button shows the group count, maximal holding weight of barbell, total count, total correct count, total wrong count, total good morning squat (down) count, total good morning squat (up) count, and hip deactivation count at each timestamp. The Upload button enables the users to upload their records to cloud. The End button writes the data into users' smartphones and terminates the exercise.

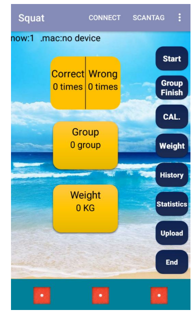

Fig. 12: The APP pages for squat exercise.

B. The statistics of workouts

To be more convenient for users to assess the effectiveness of workouts, the APP also shows the important data by line charts as shown in Figure 13. The users can select one type of data for each exercise.

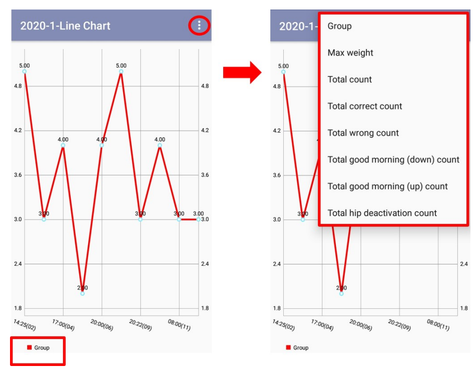

Fig. 13: The demonstration of statistics page.

C. Real-time haptic and audio feedback

For each exercise, the system offers real-time haptic and audio feedback to assist users in conducting motions. For example, the system prompts users during squat when their hips are at the same level as the knee. In the bridge exercise, the system counts down for the rest of the duration. In the double leg raise, the system also prompts when the motion is recognized. When conducting the incorrect motions, the users will receive the haptic feedback from the wearable devices.

V. User Study

We conducted an initial user study to evaluate the feedback of the wearable device. The study focused on six beginners who do not conduct the three motions (squat, bridge, and double leg raise) in their daily life or workout. The objective of the study is to observe whether the users could improve their skill of conducting the motions correctly after using the system for a period of time. The system is equipped with real-time haptic and audio feedback to report the correctness of the motion.

An expert in the field of fitness had confirmed the effectiveness of the system. Before the study, we also utilized the system to test the participants' performance when conducting the three motions. The test includes 2 groups of 10-time squats, 2 groups of 10-time bridge exercises (10 seconds each time), and 2 groups of 10-time double leg raises.

In this study, six beginners between 23 and 31 years old were recruited to the experiment. The participants were instructed to conduct the three exercises for seven days. Each day they need to finish 3 groups of 10-time squats, 3 groups of 10-time bridge exercises (10 seconds each time), and 3 groups of 10-time double leg raises. The participants were also required to operate the APP by themselves during the experiment. Then, they were asked to detail their experience with the system in a survey. After the experiment, we conducted the same test to observe whether the participants had improved their skill in performing the three exercises.

VI. Result and discussion

The testing results in TABLE IV show the accuracy of each exercise, including the tests before and after the experiment. Regarding the squat, the testing results show that 5 out of 6 participants had improved their skill of conducting the exercise. The participants revealed that it was difficult to change their motions into the correct ones instantly even if they receive the haptic and audio feedback. Because the squat is more challenging among the fitness exercise, the participants suggested that it would be better to have videos with instructions. Although it was difficult to change the motion into correct one immediately, the testing results indicate that it is possible to improve one's skill after using the system for a period of time. When the participants received the haptic and audio feedback reporting the improper parts of the motions, they tried to adjust their postures in the next turn. After continuing receiving the feedback from the system and keeping practicing the correct motions, the users can finally elevate the possibility of conducting the exercise correctly.

Regarding the bridge exercise, the testing results show that 3 out of 6 participants had improved their skill. Moreover, 2 out of 6 participants kept performing well. From the high ratio of performing the motion well, we know that it is easier for participants to conduct the exercise correctly. The feedback from the system also helped the participants to realize the incorrect motions. Thus, they can utilize the system to improve their skill and perform this exercise well.

Regarding the double leg raise, the testing results show that 5 out of 6 participants had improved their skill. The testing results also show that all participants can perform the motion well after using the system for a period of time. Thus, the haptic and audio feedback can effectively help the users degrade the possibility of conducting the exercise incorrectly.

	Squat		*Bridge*		*DLR.*	
ID	*Before*	*After*	*Before*	*After*	*Before*	*After*
1	80%	30%	90%	100%	70%	80%
2	75%	95%	80%	90%	5%	90%
3	0%	5%	100%	100%	80%	90%
4	5%	95%	95%	100%	60%	95%
5	95%	100%	100%	100%	100%	100%
6	0%	95%	100%	95%	20%	75%

TABLE IV: The accuracy of each exercise for the tests before and after the experiment. "DLR." represents Double Leg Raise.

VII. Conclusion

This paper presents a lightweight and wearable fitness system with three IMU sensors. The system can be used to recognize and judge the correctness of three kinds of exercises including squat, bridge exercise, and double leg raise. Compared with the related work with visual recognition techniques, the system with IMU can detect users' motion more precisely. The system is also portable and without space constraint. The important data recorded by Android APP can help users assess the effectiveness of their workouts. The experimental results also show that the users may improve their skill after continuing using the system for a period of time. The feedback from the system can urge the users to conduct fitness motions correctly. Thus, the chance of getting injured can be degraded during exercises. As a result, the system can play a role in long-term workouts monitoring.

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