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Digital Motion Analysis System for Rehabilitation Using Wearable Sensors

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***Abstract*—*The emergence and improvement of wearable low cost sensors gives way to an improved patient rehabilitation from impairment such as those caused by accidents or stroke. We have developed a digital motion sensing system that uses accelerometers and gyroscopes worn by the patient, and enables the rehab session to be recorded visually using a high-FPS camera. Through collaboration with interns and licensed physical therapists (PTs), we conducted tests using these wearable sensors known as the inertial measurement unit (IMU) side-by-side their norm of using a static universal goniometer (UG). An Android-based portable system was demonstrated that could be used by PTs on the move. We explored the variations of the normal range of motion (ROM) in healthy uninjured individuals, following that the functional ROM is less stringent than the conventional criteria. We can show that using the system the patient can participate in developing their digital medical records, as well as in their own wellness program*

***Index Terms*—*physical therapy, wireless inertial sensors, rehabilitation, motion analysis*

I. INTRODUCTION

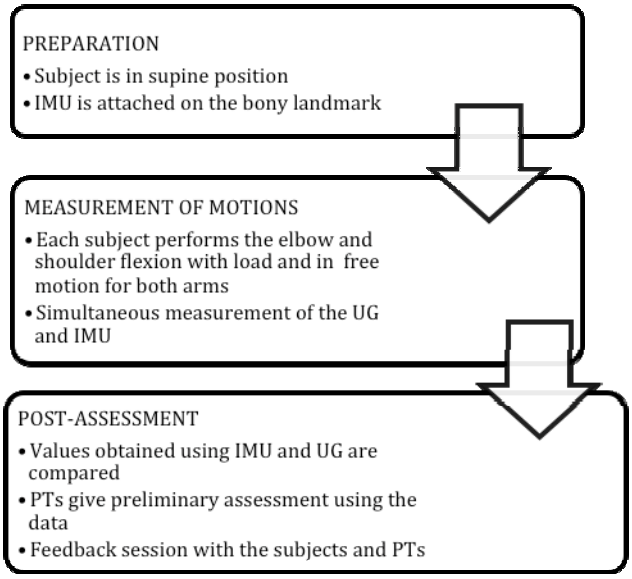
Recently, wearable devices and products have been proliferating, and innovative companies such as Apple, Samsung and Google are launching their own version of these devices. From Google glass to the Apple Watch to the Polar and Garmin fitness bands, the target markets span the whole gamut from wellness to entertainment. There is a huge potential to leverage developments in wearable sensors and technologies in other areas, such as Physical Therapy (PT) practice, especially in the evaluation of progress in PT rehabilitation programs based on measurements of range of motion.

Medical practitioners are very well trained in giving and analyzing data by conducting tests and through careful observation; however it is imperative to give an accurate assessment. Not only does the assessment rely on the skill of the practitioner but also on the device being used. As for physical therapists, one of the devices they use for rehabilitation is the universal goniometer. This device functions well as it should, although it cannot be helped that it introduces a number of errors that can affect the results. An example of the problem being faced by users of the UG is the introduction of human error, which may mean tester or recorder errors. Error can also be due to the lack of a standardized positioning or misalignment of the goniometer [2]. The meticulous care needed to use the UG also limits the frequency of measurements, for often, in three therapy session per week programs consisting of many repetitions and motions, only one of those three sessions are measurements recorded and logged.

II. REASEARCH FRAMEWORK

A. Methodology

Twelve interns from Manila Central University-College of Physical Therapy, both male and female whose ages range from 18 to 24 served as subjects. Two licensed physical therapists (PTs) served as testers, and 2 nonparticipating PT interns were the data recorders. Upper extremity joints were tested—mainly the elbow and shoulders, whose motions were done in free motion and with a light load of 2 pounds at their most convenient or relaxed pace. A 1-whole day session was allotted for the entire experiment. Measurements were done simultaneously using the digital system and the universal goniometer. The PT tester held the UG, while the IMU was attached on the bony landmarks. Found in Fig.1 is the flow of the data gathering process done.



PREPARATION
- Subject is in supine position
- IMU is attached on the bony landmark

MEASUREMENT OF MOTIONS
- Each subject performs the elbow and shoulder flexion with load and in free motion for both arms
- Simultaneous measurement of the UG and IMU

POST-ASSESSMENT
- Values obtained using IMU and UG are compared
- PTs give preliminary assessment using the data
- Feedback session with the subjects and PTs

Fig. 1. Data gathering process

B. *Motion Analysis Protocol*

The motion analysis system is divided into two protocols: Version 1 (Fig. 2) consists of the LPMS-B inertial units and a laptop that runs the LPMS Control; and Version 2 (Fig. 3) consists of the mobile version of the system where it uses the LPMS-B, a high-frame per second (FPS) camera, and an Android tablet that runs the Assistive Sensor Suite for Sports and Rehabilitation (ASSESSOR) app that controls both the IMU and camera. For this research, the IMU and camera was set to have a sampling rate of 50 Hz to compensate for the tablet's processing power. Depending on where the LPMS is going to be used, settings can be changed to match the environment. Seen in Fig. 4 are the device specifications of the IMU used in this research. A more in depth discussion for version 1 can be found in D. Oarde's work [8], and for version 2 in J.P. Azcueta's work [9].

In using the digital system, IMU was placed on the bony landmark as identified by the PT testers. The IMU communicates with the paired laptop and tablet through Bluetooth, and the data from it is exported as a .csv file, which can be later viewed using Microsoft Excel. It can give measurements from all three axes, and the data to be examined will be dependent on the orientation of the IMU.

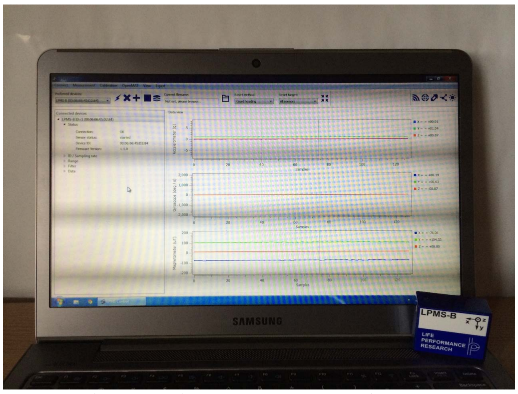
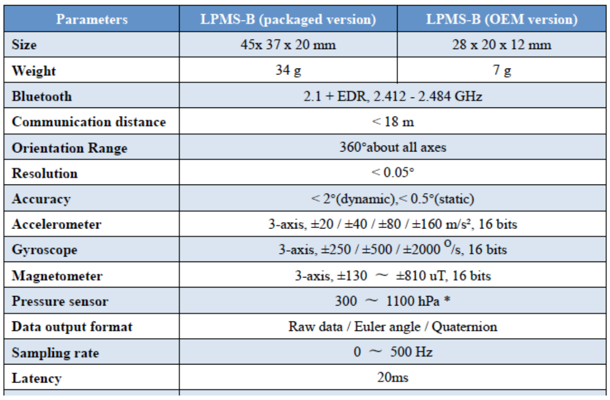


Fig. 2. Version 1 system: IMU and Laptop

Fig. 3. Version 2 system: IMU, ASSESSOR, and high-FPS camera



Parameters	LPMS-B (packaged version)	LPMS-B (OEM version)
Size	45x 37 x 20 mm	28 x 20 x 12 mm
Weight	34 g	7 g
Bluetooth	2.1 + EDR, 2.412 - 2.484 GHz	
Communication distance	< 18 m	
Orientation Range	360°about all axes	
Resolution	< 0.05°	
Accuracy	< 2°(dynamic),< 0.5°(static)	
Accelerometer	3-axis, ±20 / ±40 / ±80 / ±160 m/s², 16 bits	
Gyroscope	3-axis, ±250 / ±500 / ±2000 °/s, 16 bits	
Magnetometer	3-axis, ±130 ~ ±810 uT, 16 bits	
Pressure sensor	300 ~ 1100 hPa *	
Data output format	Raw data / Euler angle / Quaternion	
Sampling rate	0 ~ 500 Hz	
Latency	20ms	

Fig. 4. LPMS-B device specifications

III. EXPERIMENTATION

In collaboration with MCU-CPT PTs and interns, the system was used in measuring range of motion for the upper extremities alongside the UG that they use in practice. The nonparticipating interns took down measurements from both the IMU and UG. We were able to see how their usual rehabilitation session would look like when the system is used in lieu of the usual goniometer.

A. *Upper Extremity Movements*

The upper extremity movements that were taken into account were the shoulder (Fig. 5B) and elbow flexion (Fig. 5A). Each subject was asked to do the free and with load motions thrice per recording, and was done for both arms. There were only 3 repetitions of each motion so as to avoid error introduced by fatigue. In cases where pain was felt, they were asked to hold on the position or angle where they experienced pain for a few seconds, and proceed if they can.

(A) Elbow flexion

(B) Shoulder Flexion

Fig. 5. Measured movements

B. *Implementation of the System*

There were 2 phases of experimentation. The first phase made use of the laptop version, while the second phase used the mobile version with accompanying video. In both phases the PTs used the system while having D. Oarde on the side to help them interpret the data afterwards.

Version 1 of the implementation made use of the IMU and LPMS Control. While the readings from the UG were manually written down, the data from the IMU was transmitted and saved as a .csv file on the laptop. For this experiment, the orientation of the IMU had its rotation along the z-axis; therefore, the column on the Excel file EulerZ was the one of interest. Highlighting the said column and the timestamp column, a graph of the range of motion in terms of angles can be obtained. This one graph can then be used to determine how fast he or she was able to reach the peak, peak angle reached, and the duration of the measurement using the UG sine it was done simultaneously. By studying the graph the PT can also determine whether there were accessory movements that occurred such as twisting or shaking.

Similarly, Version 2 system was used in the same manner as with the previous. In this phase, the system was upgraded to a mobile version. Instead of using the laptop, the IMU was paired to a tablet that ran the ASSESSOR software, an application that correlates data from the IMU and video from a high-FPS camera. This system enabled single data and comparison of 2 data analysis.

Both systems enabled post-assessment of the session, and provided digital recordings that can be used as the subject's personal benchmark.

C. *Normal ROM Versus Functional ROM*

In practice, physical therapists refer to a set of values they use for assessing range of motion called the normative range of motion values [1]. The values looked at are those for shoulder and elbow flexion as suggested by the American Medical Association (AMA). Likewise, there is a leeway given to every measurement, where in this case an allowance of ± 10 degrees is used for evaluation. This means that if according to AMA the normal shoulder flexion is 180 degrees, if a person's measurement is between 170 to 190 degrees it is acceptable. Note that the leeway is not the same for all practitioners. This depends on their prerogative.

Ideally speaking, for a person to be called 'normal', his or her ROM measurements should fall under the criterion used. If it does not, then he or she is said to be abnormal, or further tests are to be done to rule out the possibility of abnormality. In conducting the experiment, we found out that there are several variations of the 'normal'.

Two things were observed: 1) ability to do the full ROM without experiencing pain, and 2) feeling pain at an angle. When the subjects were told to do the motions at their convenient pace, a few more things were observed: 1) the time to peak in doing the motion in free motion was faster than that with load; 2) some of the subjects' angle decreased during repetitions; and 3) there was inversion of the graph.

It was well expected to happen that the time to peak when done in free motion was faster than with load (Fig. 6). The simplest explanation for this would be because loading adds resistance to the motion. There were also cases where the peak angles decreased through repetitions (Fig. 7), where a possible explanation for this would be due to fatigue. It may be that since there were 2 testers and for each tester they have to do 3 repetitions, it is possible that their muscle 'got tired'.

Another interesting thing to note is that for some subjects, there was an inversion in the graph (Fig. 8). Strictly speaking, when the motion is done along the sagittal plane, there should be no accessory movement; however, some subjects exhibited otherwise. Upon close observation, this inversion of the graph was due to the change in orientation of the IMU (twisting of the arm) as attached on the upper arm while doing the shoulder flexion.

There were also ‘normal’ subjects who, despite being classified as normal, showed signs of pain in doing the shoulder flexion. Two out of 12 subjects reported to have pain, and were recorded accordingly. A sample of a subject who exhibited pain is S12. Shown in Table 1 are her ROM measurements executing the shoulder flexion with load. The first number indicates the angle where she felt pain, and the second is her maximum ROM. Looking at it, her measurements are below the expected range following the leeway mentioned earlier.

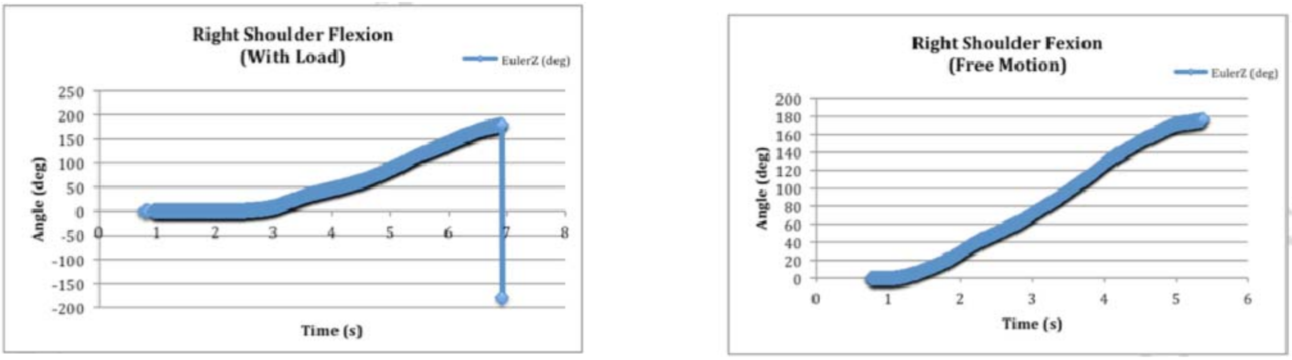


Fig. 6. Time to peak at full ROM without pain

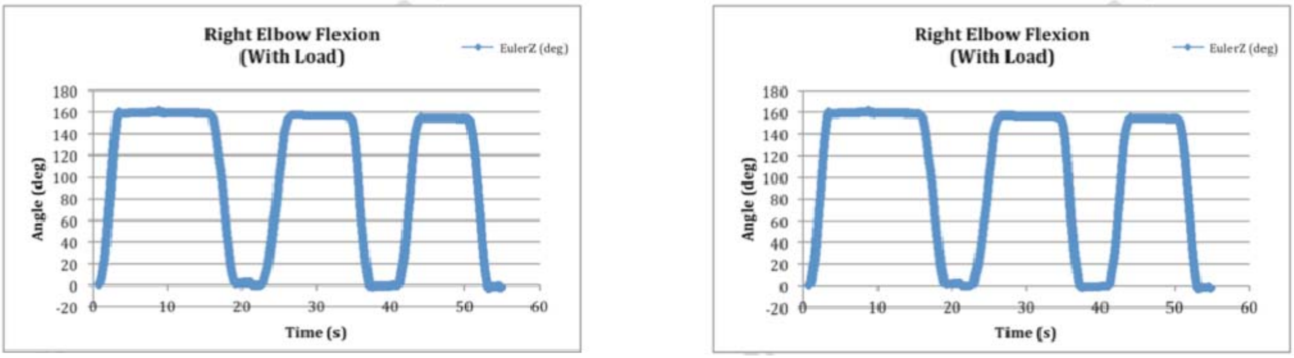


Fig. 7. Decreasing angle measurement

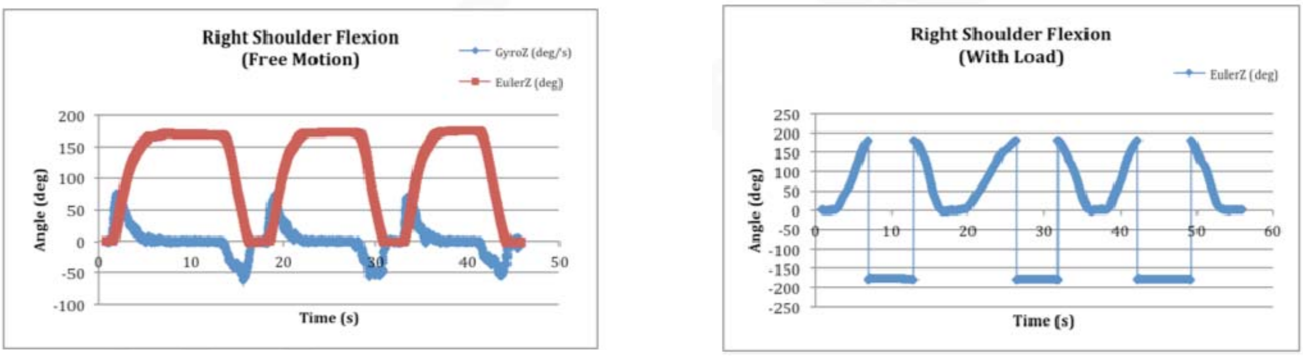


Fig. 8. Inversion of the graph due to accessory movement

TABLE I. MEASUREMENTS FOR SHOULDER FLEXION WITH LOAD OF S12 (IN DEGREES)

	UG			IMU		
	TRIAL 1	TRIAL 2	TRIAL 3	TRIAL 1	TRIAL 2	TRIAL 3
LEFT	142; 150	142; 146	146; 150	155; 166	172; 176	161; 168
RIGHT	146; 150	154; 158	150; 158	151; 157	150; 158	154; 162

TABLE II. RANGE OF MOTION VALUES FOR TESTER 1 (LEFT SHOULDER FLEXION)

REFERENCE	FREE MOTION		WITH LOAD	
	UG	IMU	UG	IMU
S01	164.000	161.000	168.000	173.000
S02	172.000	170.667	167.333	167.333
S05	165.333	168.667	170.667	174.000
S06	172.667	172.667	172.667	172.667
S07	172.000	174.333	175.333	175.333
S08	176.667	175.667	174.667	174.333
S09	175.333	174.333	175.333	176.000
S10	174.667	173.333	178.667	179.000
S12	171.333	175.333	148.667	170.000
S13	174.667	176.667	175.333	176.000
S14	172.000	169.667	169.000	169.000
S15	171.333	165.667	170.667	170.000

Looking at Table 2, the values obtained for shoulder flexion shows that a number of subjects does not fall under the range to be considered normal. If we will follow the set range (leeway of ± 10 degrees), these supposed 'normal' subjects would have to undergo other tests to see if they have abnormality that they are just not aware of, or that it is indeed their actual ROM. In some cases, normal subjects would not be able to achieve the range due to other factors such as body type [3] and flexibility [4]. This then presents a problem when dealing with actual rehabilitation patients. What if the patient, prior injury and rehab sessions, cannot reach the full 180 degrees shoulder flexion? What and where will the PTs base the rehabilitation program of the patient?

The term 'functional' pertains to the ability of the patient to do daily tasks such as dressing up, reaching overhead cabinets, and feeding without experiencing pain, which can either be assisted or done independently [6]. There are a number of tests that can be used for assessing functionality in activities of daily living; one of which is the Katz Index of Independence in Activities of Daily Living [7]. Using this test, the evaluation relies heavily on the subjective assessment of the attending therapist on whether or not the patient can execute the tasks successfully by having a scoring system. In contrast to the ideal normal ROM, functional ROM deals with the basic ability of the patient to do the tasks even if the supposed normal values is not achieved.

An example would be that 145 degrees shoulder flexion is enough for a patient to reach an overhead cabinet. We did a simulation of this motion, and found out that our subject did only 130 degrees shoulder flexion to reach the overhead cabinet, much less than that of what is expected. Clearly this means that the functional ROM of one person may vary depending on different factors such as the height of the person or the distance from the object, among others. When a patient is deemed as functional, he or she can be discharged or go back to work, and have the rehab session done independently at home.

IV. MOBILITY AND DIGITAL RECORDS

There has been a continuing movement towards improving the current medical system. Technology is slowly being introduced and incorporated to different practices and disciplines across the board. Telerehabilitation itself presents a new way of bringing the medical service to people through various system make-ups. In the future, this can shape improvements on the current system being provided [5].

Having a digital record is not limited to people undergoing rehabilitation. It can also be used by healthy individuals who wish to see, track, and evaluate their own performance through the course of training sessions.

A. *Personal Benchmarking and Progress Tracking*

By having a digital record of performance, this can serve as the individual's personal benchmark. Among its potential use are for progress tracking and assessment.

Each person has his or her own unique data; however, it is not usually taken note of. More often than not, a person's data is compared to an existing one, particularly the results based from previous studies. We should note that previous studies may have been able to deduce relevant and crucial information, but it is not representative of all. Outliers will occur, and we have to determine why and what caused it to be one. In the case of rehabilitation, not all patients undergoing the same program will have the same results. One way or another, a patient will exhibit a trait or result different to that of another patient. By being able to record this progress, the therapist will be able to review previous sessions, see trends or correlation between factors, and be able to give more feedback to the patient. Likewise, the patient will be able to see his own progress, and in turn be involved in his own wellness. In the same way as it can serve as a benchmark where if a person gets injured, if he or she has data taken prior injury, it can be the basis of the rehabilitation program. The therapist would then be able to set a more realistic goal for the patient.

B. *System Mobility*

Another capability of this system is its mobility. Compared to the usual way of accessing data by looking through piles of paper, the data can be accessed and made readily available on the device or cloud. If either or both doctor and patient are unavailable for physical consultation, using the system they can still do so.

A patient might not have to go to the doctor to have his or her statistics checked. With the help of a guardian or assistant, the patient's statistics can be measured at the comfort of his home. This presents an alternative way to patients who are too weak to leave the house. It can save both parties the time and effort in transferring from one place to another. Since the data is stored digitally, it can be sent to the doctor wirelessly, allowing the doctor to easily gain access to the data.

Likewise, if the doctor is out of town the patient can still go to the clinic where his measurements can be taken digitally. Afterwards this data can be sent to the doctor for review, and then can still give feedbacks even if the doctor is away. This gives an opportunity for both parties to maximize their time and effort in improving the patient's condition.

C. Social Impact

Rehabilitation programs are made personal to meet the needs of the patient. Having the data captured and stored digitally can also be used to compare two or more similar data between members of a group. A patient can share his or her data to another or to a support group. It opens up an avenue for discussion, feedbacks, and recognition among others.

Similarly, doctors can share their findings to their colleagues. They can use it as an additional tool in giving assessments, or use the data to prove that a certain drug or rehabilitation program is effective or not. It can then serve as a support to their claim, having the digital record as a proof.

At the moment, the Version 2 system allows sharing of data through social networking sites such as Facebook™ and Sitedrop.

V. FEEDBACK AND ACCEPTANCE

Our partner medical institution, the Manila Central University-College of Physical Therapy (MCU-CPT) was very receptive of the introduction of the system. Their initial reaction of the system was they did not really think that there is a possible alternative for their current system. Among the many feedbacks given by our participants are as follows:

- The system introduces a new approach in wellness monitoring and motion sensing;
- It helps lessen the error in taking the angle measurement;
- Would not tire out patients as much as the current method in taking measurements;
- Can elicit positive emotions to patients undergoing rehabilitation as they see their progress;
- Assessments can be done outside the four walls of the clinic or hospital;
- By having a video and IMU data correlation, it can be easier to point which muscle group is involved at the point where pain is felt; and
- It can be applied to other fields in the future such as for geriatric screening and monitoring, sports, etc.

VI. CONCLUSION

In conclusion, we have shown that wearable sensors and video data can provide a comprehensive record of a patient's rehabilitation, that patients can be more involved in their own wellness by using personal sensor units, and contributing to daily buildup of medical record of exercises and therapies throughout recovery. It is now possible using this integrated sensor system and medical records database for therapists, doctors and patients to have longitudinal time series of data (graphs with synched video) from pre-injury baseline, post injury, rehabilitation, to recovery and return to normal function. By measuring the range of motion required for activities of daily living with this system, we can help doctors and therapists' transition patients back to work. Patients whose range of motion falls within the normal range of motion can be considered functionally ready.

The rehabilitation program at its current state can be said as more practitioner-oriented. This means that most, if not all, assessments rely heavily on what the doctor or therapist can see and measure at that instant, and what he or she can recall from the previous sessions. By proposing this upgrade of the system, the rehabilitation program becomes practitioner and patient-oriented system. The assessments can be based not only from the visual and subjective analysis from the doctors or therapists, but also from the personal assessments of the patient. Moreover, it gives the patient the power to control his or her own program, to fit the need and drive to improve.

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