GonioSense: A Wearable-Based Range of Motion Sensing and Measurement System for Body Joints

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ABSTRACT

This paper introduces GonioSense – a wearable based system that can track and measure both active and passive joint motions. GonioSense leverages embedded inertial sensors to provide reliable and consistent measurement results. A key challenge for our system is how to efficiently detect body movement and accurately calculate range of joint motion. We built a preliminary version that can collect and analyze sensor data in real time on the Android platform. To test the system, we recruited five healthy volunteers and measured six kinds of joint motions. The same tools used by physical therapists, measurements gathered from a goniometer and an inclinometer is what we used as the ground truth data for calibrations and evaluation of our algorithm. In the initial version, GonioSense estimation errors are within ± 5% for more than 80% cases. By utilizing wearable technology, the benefits for both doctors and patients could bring forth an immense step forward in physical therapy treatment.

Keywords

Wearable; Joint motion; Inertial measurement unit sensors; Internet of Things

1. INTRODUCTION

Beginning around age 30, the human joint functions become more restricted. This is due to muscle loss, changes in cartilage, and variations in connective tissue. The result of these changes will increase stress on certain joints, make the joint less resilient, and be more susceptible to damage [3]. The impairment of joint function and rehabilitation status are mainly assessed by measuring range of joint motion. Traditionally, range of motion (ROM) should be evaluated with a goniometer/inclinometer by a physical therapist [4]. One of the drawbacks of the conventional tools is that they must be held with two hands. This leaves neither hand free for stabilization of the body or joint [4]. Physical therapist lacks an efficient way that can provide reliable and consistent measurement results.

MobiCom'16 October 03-07, 2016, New York City, NY, USA

ACM ISBN 978-1-4503-4226-1/16/10.

DOI: http://dx.doi.org/10.1145/2973750.2985268

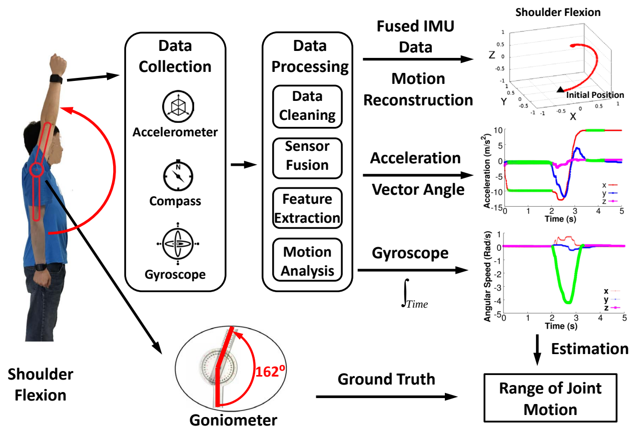

Figure 1: An overview of GonioSense. IMU data is collected using a smartwatch on subject's wrist. Joint motion will be detected and reconstructed based on the recorded data. Meanwhile, the shoulder joint motion is measured using a goniometer, which serves as ground truth.

Among all the off-the-shelf portable devices, wearables, such as smartwatches, have their own advantages. For example, people wear it throughout the day, therefore it is possible to continuously collect an individual's activity information. This unique characteristic enables a wide range of healthcare applications including sleep monitoring, behavioral disorders detection, and elderly support.

Our proposed system, GonioSense, takes advantage of motion sensors built into smartwatches to detect joint motion and measure ROM. Our approach relies on the inertial measurement unit (IMU) sensors to infer 3D orientation and rotation information. GonioSense overcomes the drawbacks of the traditional measurement methods from the following three aspects. First, GonioSense does not require different tools to measure different joint motions. Second, it will not generate examiner judgment errors. Last, it can provide accurate and consistent measurement results over time.

2. GONIOSENSE DESIGN

In this section, we describe the architecture of GonioSense and present primary analyzing techniques.

Preliminary: In this work, we choose to use smartwatch as the sensing platform and only focus on measuring shoulder and elbow joint motions. According to [4], we choose the six most common joint motions as examples to demonstrate

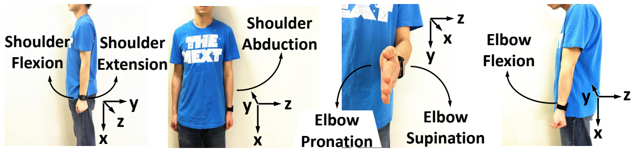

Figure 2: Six different shoulder and elbow joint motions and the corresponding arm and smartwatch initial positions.

the efficacy of our system. The six joint motions are shoulder flexion, extension, and abduction; elbow flexion, supination and pronation (Figure 2). We believe this system can also be used to perform lower-extremity joint motion measurements, e.g. wearing it on ankle.

System Design and Implementation: Our system has two modules, a front-end sensing module that records sensor data, and a back-end modeling module to reconstruct the joint motion and estimate ROM values. The sensing module collects data during the measurement process and stores the data into local databases. The modeling module can analyze data in real time as well as offline. We implemented a preliminary version of GonioSense on the Android platform. There is a phone application that runs on an LG E980 Android phone [1] as well as a companion app that runs on a Sony SmartWatch 3 [2]. The sensing module receives sensor data from the smartmatch and stores those data into SQLite database on the smartphone. Three types of sensor data are recorded into database, namely they are acceleration, gyroscope and magnetic field. The sampling frequency is set to $100Hz$. The data modeling module running on the smartwatch determines the joint motion and estimates ROM values. The ground truth of each joint motion is measured using either a goniometer or an inclinometer.

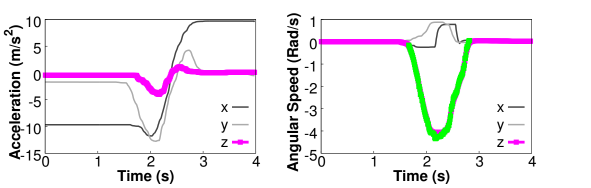

Figure 3: Recorded accelerometer and gyroscope data of shoulder flexion. The smartwatch is rotating around the z-axis.

Motion Detection and Reconstruction: IMU sensors can detect movements in x, y and z-axis regardless of the orientation of watch. For each joint motion, the smartwatch is actually rotating around a single axis, and the ROM value can be calculated by integrating the gyroscope values of that certain axis. Suppose we are measuring shoulder flexion ROM described in Figure 2, the arm wearing smartwatch is rotating around z-axis of smartwatch. During this process, the accelerometer readings along the z-axis should stay somewhat stable compared to those of the other two axis. Based on this fact, we develop a threshold-based method to determine which axis the smartwatch is rotating around. Further we need to infer which motion it is being measured. Our algorithm calculates the standard deviation of acceleration values along each axis, and sets up a threshold to filter out the axis which has the smallest standard deviation. Figure 3 shows the smartwatch is moving around the z-axis for shoulder flexion.

3. EVALUATION

There are two types of ROM, passive range of motion (PROM) and active range of motion (AROM). PROM is the arc of motion attained by an examiner without assistance from the subject, while AROM is the arc of motion attained by a subject during unassisted voluntary joint motion.

In this experiment, we measured the subject's active and passive ROM using goniometer/inclinometer for each motion. These measurements serve as ground truth for comparison with estimated ROM. Figure 4 shows the cumulative distribution function (CDF) of active and passive ROM estimation errors. The results show that around 80% of the time, the estimation error is within a $\pm 5\%$ interval for AROM. For PROM, around 70% of the time, the estimation error is within a $\pm 5\%$ interval. The overall accuracy of PROM is not as good as AROM, but our system is still reliable for most cases. The reason for this deterioration is when doing the measurement, the examiner needs to feel the barrier that stops further motion. This will cause some noticeable shaky movements and vibrations during the measurement process, which will add extra noise to received data.

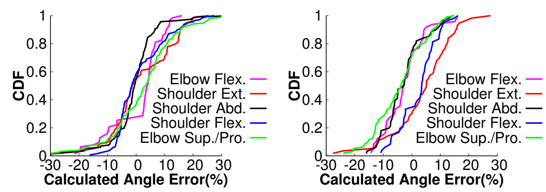

Figure 4: The CDFs of active (left) and passive (right) ROM estimation error.

4. SUMMARY AND FUTURE WORK

Our work proposes a wearable based system that can help physical therapists on joint motion measurements. The evaluation results show the current system can accurately measure both active and passive joint motions. While our current system demonstrates both feasibility and preliminary usefulness, numerous challenges remain. They include: (i) mechanisms to improve joint ROM value estimation accuracy; (ii) algorithms that can identify more joint motions; (iii) testing system performance in hospitals, with patients having different joint injuries.

5. ACKNOWLEDGMENTS

We sincerely thank the reviewers for their feedback. We also thank all the volunteers for participating in this project.

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