Automatic Measurement of Pronation/Supination, Flexion/Extension and Abduction/Adduction Motion of Human Limbs using Wearable Inertial and Magnetic Sensors

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***Abstract*—This research deals with the design and programming of devices for measuring automatically human motion using portable and low-cost technologies. The movements studied in this research are pronation/supination, flexion/extension and abduction/adduction of the upper and lower limb, which are required for a number of activities of daily living. A home-made attitude and heading reference system based on inertial and magnetic sensor is presented. It was compared with a similar device available in the market, and with respect to a video-camera based system used as gold standard. An experimental platform was also built for controlling and replicating experiments. The results obtained by the proposed device are competitive and promising with a general performance comparable to a commercial device.**

Keywords- ubiquitous healthcare; real-time medical data collection; systems for measuring tissue parameters.

I. INTRODUCTION

This research focuses on designing automatic methods and technologies for long-term and continuous monitoring of human motion related to functional activities of daily living, namely pronation/supination flexion/extension and abduction/adduction of upper and lower limbs.

The pronation/supination describes the motion of a radioulnar articulation such as the wrist and comprise the pronation or internal rotation, and the supination or external rotation, palm-down and palm-up for the wrist, respectively. The flexion/extension describes the motion around a hinge joint such as the elbow and comprise the flexion, a bending movement that reduces the angle between the segments linked by the joint, and the extension or straightening movement that increases the angle between the linked segments. The abduction/adduction describes the motion away and towards a midline, such as the axis of the body, it comprises the abduction or movement of arms or legs, for instance, out to the side, and the adduction or movement to bring the limbs back in.

The movements of pronation/supination and flexion/extension are required for a number of activities of daily living such as feeding, handwriting, typing, picking up and holding objects, just to mention examples involving the upper limb [1], whereas abduction/adduction of the lower limb plays an important role in activities such as walking and running. In general, these movements are important when assessing functional abilities, determining therapeutic intervention or athletic programs for enhancing skills, and are also relevant signs for neuromotor development and neuromotor function associated with aging [2].

The measurement of pronation/supination, flexion/extension and abduction/adduction for assessing functional abilities relies commonly on both, goniometric measurements and the observation of physicians and trained therapists, that do not ensure a uniform assessment.

Nowadays, portable inertial and magnetic sensors as well as powerful, inexpensive and tiny micro-processors enable the development of wearable technologies for measuring movement related to functional abilities on a long-term and continuous basis. Also, these conditions offer a unique opportunity to reach broad segments of the population. These devices are known as Attitude and Heading Reference Systems (AHRS).

It is worth to mention that commercial AHRS present two main drawbacks. First, they are developed as black boxes, offering limited possibilities for extending or adapting them to user's needs. And second, commercial AHRS are usually general-purpose devices that are not specifically intended for measuring human motion. Therefore, we strongly believe that developing a home-made AHRS is a way to overcome these limitations.

This article describes the design of a home-made AHRS (HM-AHRS) using inertial and magnetic sensors. The HM-AHRS is programmed to automatically estimate its orientation from which a joint angle is deduced. It was evaluated using a set of tests of pronation/supination, flexion/extension and abduction/adduction movements. A specific platform for conducting these tests was built. Eight people participated in the tests; they worn both our HM-AHRS and a commercial AHRS, a LPMS-B device (LP-research, Japan). Simultaneously, movements of individuals were tracked by a video-camera based system. Our HM-AHRS obtained competitive results.

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The main contribution of this research is the implementation of an AHRS device from the scratch with a performance comparable to a commercial AHRS in the measurement of human motion, namely pronation/supination, flexion/extension and abduction/adduction of upper and lower limbs. This is a challenging problem and it also poses issues such as the lack of external references, the deformation and stress of soft tissue, and the noise and drift that usually affect inertial sensors.

The rest of this paper is organized as follows: Section II revises the most significant related work. Section III describes the design, implementation and programming of our HM-AHRS. Section IV presents and discusses the results that were obtained. Finally, Section V gives concluding remarks and some perspectives of this research.

II. RELATED WORK

In this section we briefly revise significant related work.

Lee et al. [3] designed an array of accelerometer-based nodes to measure flexion/extension of upper limb. Their device is tested first on a programmable rotary stage and then compared to an electro-mechanical goniometer in experiments involving one individual. The power consumption of the nodes and communication issues are also investigated in this research. Namely, the latency of a system comprising various nodes for measuring simultaneously multiple joints is calculated with interesting results.

El-Gohary and McNames [4] combined two inertial measurement units containing each one a triaxial accelerometer and a triaxial gyroscope, and kinematic models to control robotic manipulators to estimate human joint angles. The proposed method was tested for pronation/supination movement of the forearm, abduction/adduction movement of the shoulder, and flexion/extension of the elbow, using eight subjects performing normal and fast movement. Also, it was evaluated against an optical reference system with good results. A similar solution was studied by Zhou et al. [5].

Zhang et al. [6] focused on the problems of inertial drift and acceleration interference that affect inertial and magnetic sensors. They proposed schemes for filtering and data fusion, and conducted tests for tracking motion of upper limb using an array of three units of triaxial inertial and magnetic sensors. The outcome of the proposed method in represented as quaternions, that are directly compared to the outcome of a reference system, a BTS SMART-D optical motion tracker (BTS BioEngineering, Italy) involving one individual.

Kaneko et al. [2] developed a portable evaluation system for pronation/supination movement of the forearm using four wireless inertial sensors. From the obtained measurements reference curves for both, neuromotor development for children and changes in neuromotor function for adults are obtained. Even though the cited system has been extensively tested, with several hundreds of subjects, any alternative device or system is considered to compare its performance.

Bonroy et al. [7] developed a brace to measure flexion/extension movement of the knee using two accelerometers and one inductive sensor for static and dynamic measurement, respectively. These measurements are used to classify physical activities of ten healthy subjects, such as walking, ascending and descending of stairs, and fast locomotion. Previously, the system was compared against a Vicon optical motion capture system (Vicon Motion Systems, UK) with competitive results. However, the authors focused on classifying activities based on pattern detection in form of peaks.

Lambrecht and Kirsch [8] implemented an AHRS module using inertial and magnetic sensors. Two variations of AHRS were tested, one relying only on inertial sensors and one relying on both inertial and magnetic sensors, and compared against an active-marker motion capture system, Optotrak Certus (NDI, Canada). The range of movements tested in this research is wide and comprises seven degrees of freedom of upper limb, *i.e.*, azimuth, elevation and internal rotation of shoulder; elbow flexion; forearm pronation; and flexion and deviation of wrist. The results that were obtained are very good, however tests were conducted using only one individual.

In contrast to previous work, four important features of our system can be highlighted: (1) it relies only on one inertial and magnetic measurement unit; (2) the same method is used to measure pronation/supination, flexion/extension and abduction/adduction of upper and lower limbs; (3) its performance is compared with an analog device and with respect to a gold standard based on a video-camera tracking system; and (4) it was tested with a group of people, in this case eight individuals.

III. MEASUREMENT OF PRONATION/SUPINATION, FLEXION/EXTENSION AND ABDUCTION/ADDUCTION

This section is divided into two parts. The first one provides technical details of the instruments used in this research and describes also the experimental settings. The second one summarizes the methods and algorithms that were programed in our HM-AHRS.

A. *Setup*

This part describes the physical components and conditions of the experiments conducted for our research.

1) Measurement Instruments: Two different devices AHRS were used, our HM-AHRS and a LMPS-B. A video-camera based system to calculate ground truth values was also used. Both AHRS devices as well as the video-camera based system operate with a sampling rate of 50 Hz. In all the experiments described in this research both devices AHRS were worn simultaneously by the subjects, and meanwhile the experiments were recorded by the video-camera based system. More specifications of these instruments are detailed below.

- HM-AHRS. The Home-Made Attitude and Heading Reference System comprises an ArduIMU v3 (3D Robotics, USA) with three different MEMS sensors (3-axis gyroscope, 3-axis accelerometer and 3-axis magnetometer), on-board Atmega328 microprocessor running at 16MHz, bluetooth RN-42 communication module for distances up to 20m, and a lithium battery of 3.7V at 1000mAh. The approximate weight of HM-AHRS is 35g.
- LPMS-B. The LP-Research Motion Sensor Bluetooth version is a miniature wireless inertial measurement unit (IMU) / attitude and heading reference system (AHRS). This device includes three different MEMS

sensors: 3-axis gyroscope, 3-axis accelerometer and 3-axis magnetometer. Its communication distance scope is 18m, it has a lithium battery of 3.7V at 800mAh, and it weights 34g.

- Video-camera based system. The video system consists of both, video-camera and tracker software. The video-camera is a Nikon D5200 with 24.1MP CMOS sensor and Full HD (1900×1080p) video recording. The tracker software is a free video analysis and modeling tool built on the Open Source Physics (OSP) Java framework, able to track a visual mark and calculate its orientation with respect to a given axis.

2) Experimental settings: To perform pronation/supination, flexion/extension and abduction/adduction tests, an experimental platform was designed and built. It consists of a translucent rectangular frame of 80×80cm and a weight of 3kg, with a rotatory circular plate in the middle with visual marks and limit stops (see Figure 1(a)). These stops can be manually adjusted and set on arcs of 30 and 60 degrees. Additionally, the rotatory plate has three handles for short frontal (pronation/supination test of forearm), short lateral (flexion/extension test of forearm and shank) and large lateral (flexion/extension and abduction/adduction tests of arm and thigh) movements, as illustrated in Figures 1(b), 1(c), 1(d).

A sketch of the general setup involving the measurement instruments and the experimental platform used in our research is given in Figure 2. It is important to notice that all estimations are made locally by AHRS devices, and the server is only in charge of data acquisition for further comparison.

B. Methods

1) Subjects and conditions: Eight asymptomatic subjects participated in the tests, 6 men and 2 women, with a mean age of 27.3 (±5.07) years, and a height of 1.69 (±0.08) m. All subjects gave their informed consent to participate in these experiments.

Both AHRS devices were placed on the forearms of test subjects using an adjustable elastic band with axes manually aligned previously using a mechanical goniometer. To neutralize the movement of the shoulder a belt attached to the body at the level of the breast was used.

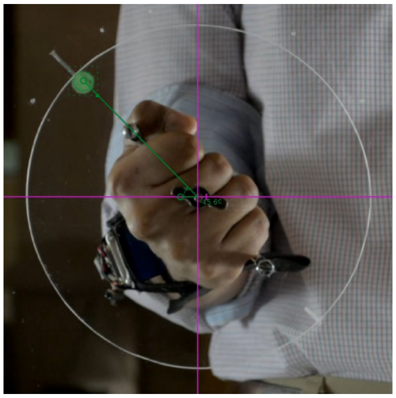
Since both devices are wireless there is no need of additional cables that might obstruct the movement of the limbs.

Each subject performed two sets of movements for these: pronation/supination of the forearm; flexion/extension of forearm and arm; flexion/extension of thigh and shank; abduction/adduction of the arm and thigh.

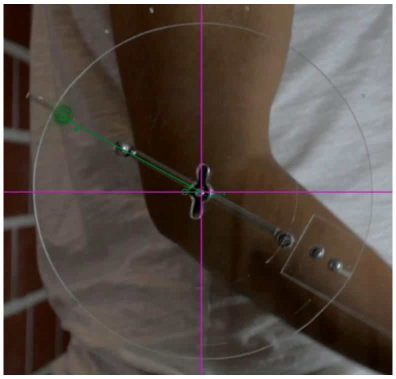
For the first set of movements involving upper limb, subjects were asked to repeat systematic movements within an arc of 60 degrees at normal speed, and for those involving lower limb, subjects were asked to repeat systematic movements within an arc of 30 degrees at normal speed. For the second set of all sort of movements, subjects were asked to perform freely movements at their own pace. These movements were performed by the subjects in random order.

Since all the instruments utilized to measure angles operate independently, a post-processing for synchronizing datasets was applied. A controlled start time for each instrument was

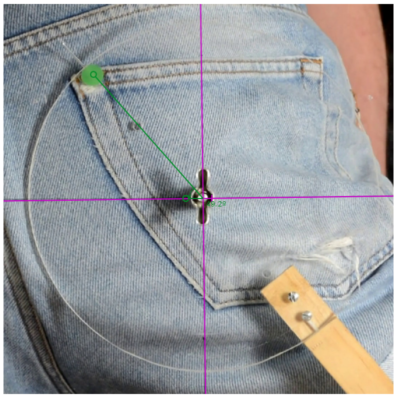
(a) Experimental platform



(b) Pronation/Supination test



(c) Flexion/Extension test



(d) Abduction/Adduction test

Figure 1. Details of the experimental platform and measured movements.

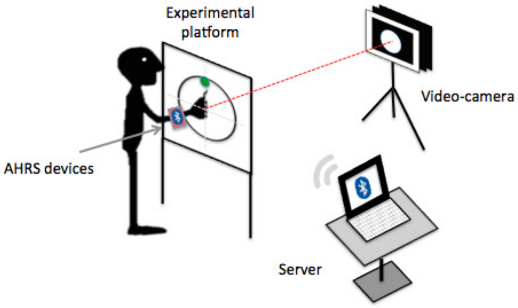


Figure 2. Setup of experiments.

established, for aligning independent signals in function of time; the start time was also used to adjust the initial magnitude of the instruments, 90 degrees for pronation/supination and 0 degrees for flexion/extension and abduction/adduction tests.

2) Algorithm: Inertial and magnetic sensors comprised in AHSR devices calculate linear acceleration, angular velocity and magnetic fields. Even though calculating angles from these values is possible, by applying for instance a straightforward integration of multiple readings of linear acceleration, the resulting value is subject to inaccuracy, specially over long periods of time. In effect, these sensors produce highly variable signals and they are susceptible to noise, for instance accelerometers and gyroscopes are affected by drift whereas magnetometers are affected by magnetized objects.

To the previously mentioned technical limitations of the sensors of AHRS devices, two issues that increase the complexity of the problem of measuring pronation/supination, flexion/extension and abduction/adduction motion must be also considered. The first one is tracking moving objects without any external reference to which the system can be tied. And the second is measuring motion of objects affected by deformation and stress of soft tissue.

For these reasons, algorithms for AHRS devices typically combine evidences provided by both, inertial and magnetic sensors, to improve the accuracy of estimations, and apply self-calibration and filters to reduce or compensate noise. This is also the way in which our AHRS has been programmed, which is based on complementary filtering.

Our algorithm is divided into three main stages: (1) calibration, (2) estimation, and (3) correction. The algorithm is sketched in Figure 3 and the main stages are described below.

- **Calibration**. For calibrating inertial sensors they must be exposed to various situations and then measure the actual error.
  In our case, the calibration of the accelerometer is done in this way, the sensor is moved gently in all possible orientations. For each axis, the maximum and minimum values from the obtained readings are identified, a range and the mean of the range are determined from these thresholds. Next, the error or offset is calculated by subtracting the mean to the known value of gravity, that is 1g. Once calculated the offset it will be subtracted from the raw readings from the accelerometer.
  For the calibration of the gyroscope an average of readings while the sensor is static is first calculated, the offset. Then, the offset is subtracted from the raw readings from the gyroscope.
  The calibration of the magnetometer to reduce the distortion of the magnetic field is a bit more intricate than previous ones. It comprises one similar step where the sensor is turned in all possible orientations and then an average error or offset is calculated for each axis. The second step requires the calculation of a rotating matrix to multiply the actual readings of the sensor, distributed in the shape of an ellipsis, and transforming the distribution into a sphere. These steps are known as correction of hard and soft iron errors, respectively.
  The stage of calibration is made once (step 1 of the algorithm) and must be recalculated each time the experimental conditions have changed.
- **Estimation**. In this stage, a first calculation of angles is performed. Since this calculation is inaccurate and is revised in a next stage, these values are considered as “estimations”.
  In our case, the initial readings from sensors are obtained (step 2). From the readings from the accelerometer and magnetometer, a rotation matrix known as the Direction Cosine Matrix (DCM) is calculated (step 3). Then the rotation matrix is updated using the readings from the gyroscope (step 4). The readings from the gyroscope are integrated taking into account a measurement error (Me). Initially Me is equal to 0 and is updated in a subsequent stage. Finally, the rotation matrix is normalized to preserve its orthogonality (step 5).
- **Correction**. In this stage, estimations are corrected by applying known error models of the sensors.
  In our case, the drift error is corrected by using the readings from both, accelerometer and magnetometer, taking into account known errors of these sensors (step 6). In our algorithm, this value was obtained from the data sheet of the sensors. With these values, the measurement error Me is updated (step 7). Then Euler angles are calculated from the rotation matrix (steps 8 and 9).

The stages of estimation and correction are alternated from now on from step 2. The measurement error calculated in step 7 becomes the known error in the next iteration.

IV. RESULTS AND DISCUSSION

One hundred and twelve sets were processed in total (16 for the experiments of pronation/supination, 64 for flexion/extension, and 32 for abduction/adduction), all comprising the angles calculated by three sources: (1) the commercial AHRS, a LPMS-B device, (2) our HM-AHRS, and (3) the video-camera based system or gold standard.

The root-mean-square error (RMSE) between the estimated values of AHRS devices and the ground-truth values, as well as the Pearson product-moment correlation coefficient (PCC) for the same values were calculated. Tables I, II and III summarize the results per treatment (arcs of 60 degrees for upper limb and 30 degrees for lower limb, and also free movements for both limbs).

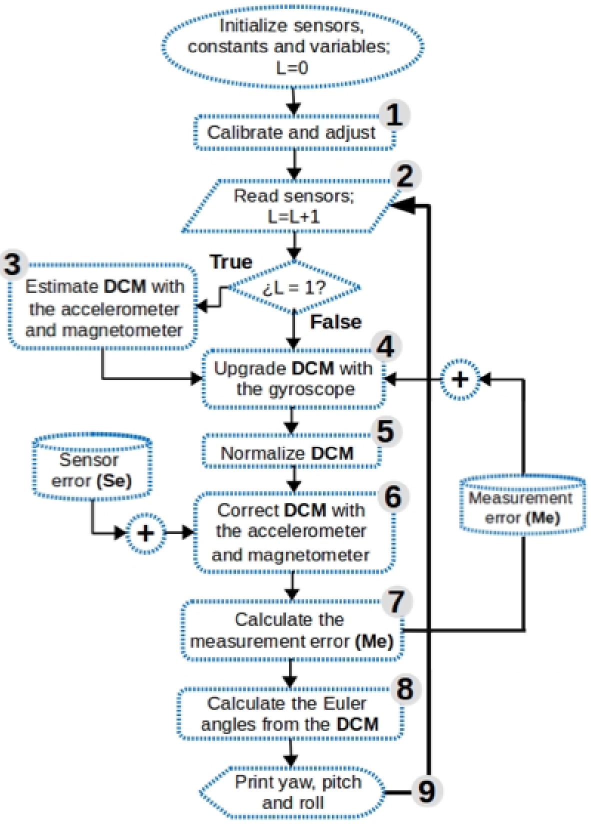


Figure 3. Algorithm used to calculate AHRS orientation, and then angles of pronation/supination, flexion/extension and abduction/adduction movements. L is an index of iterations.

Two remarks can be highlighted from these tables. First, there is a very good agreement between the estimations made separately by independent devices with respect to the ground-truth values, as can be seen in the high correlation between the compared values (columns PCC). Second, the performance of both AHRS devices is quite similar, according to the mean error calculated for treatment (columns ^{o}RMSE).

On average, the LPMS-B device is up to 0.35 angle more accurate than the HM-AHRS device for small arcs (30^o) for all treatments, whereas for larger arcs (60^o and free movements) the scores of both devices are close. There is a difference of up to 0.55 and 1.13 degrees for movement within arcs of 60^o and free movement, respectively.

These results were obtained from experiments that lasted short periods of time, as usually required for assessing functional activities in laboratories. Longer tracking periods are more prone to errors and noise, and more sensitive self-calibration methods and filters must be designed for correcting these drawbacks and enabling AHRS devices for daily uses.

However, it is worth to remark that our HM-AHRS achieved a performance comparable with a commercial AHRS, according to a video-camera based system using a standard software for optical tracking.

TABLE I. RESULTS OF PRONATION/SUPINATION EXPERIMENT. IN THE COLUMN $Treatment$, f STANDS FOR FOREARM.

	LPMS-B		HM-AHRS	
Treatment	^{o}RMSE mean (SD)	PCC	^{o}RMSE mean (SD)	PCC
f/60^o	4.81 (0.98)	0.98	4.62 (1.03)	0.99
f/Free	9.78 (2.42)	0.99	9.11 (1.78)	0.98

TABLE II. RESULTS OF FLEXION/EXTENSION EXPERIMENT. IN COLUMN $Treatment$, f STANDS FOR FOREARM, a FOR ARM, t FOR THIGH AND s FOR SHANK.

	LPMS-B		HM-AHRS	
Treatment	^{o}RMSE mean (SD)	PCC	^{o}RMSE mean (SD)	PCC
f/60^o	2.35 (0.59)	1.00	2.90 (0.59)	1.00
f/Free	3.63 (0.85)	1.00	4.76 (2.04)	1.00
a/60^o	2.51 (0.61)	0.99	2.32 (0.66)	1.00
a/Free	3.63 (1.04)	0.99	3.26 (0.97)	1.00
t/30^o	2.30 (0.73)	0.99	2.56 (0.71)	0.98
t/Free	2.79 (0.81)	0.99	2.91 (0.80)	0.99
s/30^o	1.57 (0.50)	0.99	1.63 (0.45)	0.99
s/Free	2.60 (0.47)	0.99	2.98 (1.04)	0.99

TABLE III. RESULTS OF ABDUCTION/ADDUCTION EXPERIMENT. IN THE COLUMN $Treatment$, a STANDS FOR ARM AND t FOR THIGH.

	LPMS-B		HM-AHRS	
Treatment	^{o}RMSE mean (SD)	PCC	^{o}RMSE mean (SD)	PCC
a/30^o	2.17 (0.49)	1.00	2.37 (0.94)	1.00
a/Free	3.30 (0.99)	1.00	2.69 (0.97)	1.00
t/30^o	1.79 (0.43)	0.99	2.14 (0.61)	0.99
t/Free	1.96 (0.51)	0.99	2.19 (0.69)	0.99

V. CONCLUSION AND PERSPECTIVES

The design of an HM-AHRS device for measuring human motion is presented. Designing and programming our own tool is a decision made by our group to address the complex problem of measuring angles of human motion.

The HM-AHRS device relies on inertial and magnetic sensors, and a simple complementary filter running on a microprocessor embedded in the device. The HM-AHRS was tested with a group of real people for measuring pronation/supination, flexion/extension and abduction/adduction movements of the upper and lower limbs. It was compared to a commercial AHRS device from LP-research, and with respect to ground-truth values provided by a video-camera based system. An experimental platform was also designed and built for controlling and replicating experiments.

The results obtained by our device are very competitive, with a general performance comparable to a black box based on a commercial device.

The device described in this article is part of an ongoing research whose goal is to design reliable and low-cost devices for enhancing human-computer interaction for applications such as serious games, exergames, and interfaces for rehabilitation systems. In all these examples, the proper measurement of pronation/supination, flexion/extension and abduction/adduction movement of upper and lower limbs is considered crucial for designing reliable technologies.

In the near future, we will work on the improvement of filters to better track human motion over longer periods. For that, more complicated filters such as Kalman filter is considered.

We will extend our work to combine the estimations made by pairs of our HM-AHRS device in order to calculate joint angles in which both anatomical references are dynamic, *i.e.*, for knee angle two AHRS devices are placed on thigh and shank, and angles are measured while both segments are in movement. These studies involve significant computational challenges, such as writing simple algorithms for local computation, establishing real-time communication among various AHRS devices, improving calibration, and incorporating sensors and methods for self-detecting a proper alignment of various devices, among others.

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