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Preliminary tests of an Inertial Measurement Units based System for Spine mobility assessment in patients with Ankylosing Spondylitis

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***Abstract*— This paper presents the preliminary tests of a novel system prototype for the physical assessment of mobility in patients with Ankylosing Spondylitis (AS). The system combines multi-inertial sensors arrays with Kalman Filters-based pose estimation for monitoring spine mobility in patients with AS. This system allows detecting movements with more reliable information than the manual clinical evaluation.**

I. INTRODUCTION

The group of rheumatic diseases includes at least two hundred specific disorders that all together are one of the major causes of morbidity in the general population worldwide. Ankylosing spondylitis (*AS*) belongs to the group of rheumatic inflammatory diseases named spondyloarthropathies [1].

AS primordially affects the articulations of the axial musculoskeletal system, including the spine, the sacroiliac joints, and entheses (tendon and ligament insertion zone), followed by hip, shoulder, and peripheral articulations. The primary affections to the musculoskeletal system involve: 1) rigidity of the spine (higher at physical rest); 2) persistent back pain and lumbosacral inflammation; 3) severe inflammation of the sacroiliac joints (sacroiliitis) [2].

Some studies have estimated that the prevalence of AS in the Mexican population is around 0.6% to 0.9% of the population. Burgos-Vargas et al. [3] reported that the incidence of new cases of SpA in their study population relies mainly on young adults between 16 to 30 years. Other studies reported a rate of 5:1 of affections in males against women.

At present, the diagnosis is usually delayed and even may take years for its detection; the current medical tests include blood tests, medical imaging, and physical evaluation. The spinal joint and the sacroiliac articulations assessment is essential to know the patient's state and the progress of the ailment or the response to treatment [4].

For the evaluation, self-perception of pain, functional capacity, and inflammation questionnaires are used. In

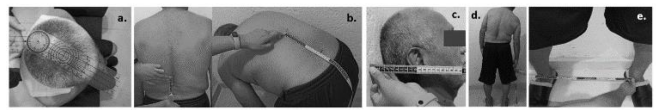

Figure 1. BASMI measurements. a) cervical rotation. b) Modified Schober Test. c) tragus to wall distance. d) Lumbar side flexion. e) Intermalleolar distance.

addition, five mobility parameters are evaluated; these are included in Bath AS Metrology Index (*BASMI*), the most used index to assess AS patients. Measurements contemplate cervical rotation, tragus to wall distance, lumbar side flexion, modified Schober Test, and intermalleolar distance (Fig. 1) [5].

An expert operator applies the *BASMI test* by using measuring tape and goniometers to obtain the measures. Thus, systematic, and subjective errors could appear due to the operator experience, the correct use of the mentioned instruments, the patient's erratic movements during the test, or observation errors. For all these, measurements lack accuracy, repeatability, and sensibility to changes is suspected according to some studies [6][7].

Recently, some research works to assess AS patients using inertial systems have been reported. Li, X. et al. [8] reported the validity of using a single inertial sensor to evaluate the cervical spine inclination and rotation. Fathi, et al. [9] used three Shimmer brand inertial sensors, to detect incorrect postures of AS patients; also, Aranda-Varela, et al. [10] used three Shimmer brand inertial sensors to assess first the cervical spine mobility and separately then the mobility of the lumbar spine. Aranda-Varela, et al. [11] established the IUCOASMI index, correlating the BASMI with their obtained metrics using two ViMove brand inertial sensors.

Even though the mentioned works provide precision and repeatability to the measurements, they use only two or three sensors at most, limiting the amount of information they can provide for fine and complex movements due to the complexity of the ailment; furthermore, the evaluation only considers ranges of motion in the lumbar spine. To face these limitations, the present work proposes a novel system for

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mobility involving the thoracic and lumbar spine. The system comprises six inertial sensors, three for the thoracic spine and three for the lumbar spine, providing more information than similar reported systems.

II. METHODOLOGY

A. Movement Estimation

The proposed system comprises six small inertial sensor units, whose size has been designed specifically for spine motion assessment. Each sensor contains a tri-axial accelerometer, a tri-axial gyroscope, and a tri-axial magnetometer. The sensors are placed along the patients' thoracic and lumbar spine to evaluate their movements in the sagittal and coronal planes by kinematic segments, using an algorithm based on Kalman Filters (KF). Each segment's orientation is first predicted using the gyroscopes and then corrected by the spatial reference provided by the accelerometers (Fig. 2).

The orientation estimation of the sensors can be translated as the estimation of the change of the roll, pitch, and yaw angles; considering the location of the sensors, it must be the rotation in the x, z, and y-axis, respectively (Fig. 3b). However, it is only necessary for this work to estimate the roll and pitch angles for the evaluation of frontal and lateral flexions of the spine.

Based on Lee et al. [12] and Ligorio & Sabatini [13] works, an algorithm that accurately determines the roll and pitch angles under dynamic conditions was implemented. The algorithm aims to estimate the vector ${}^{S}Z$ from the rotation matrix ${}^{I}_{S}R$, which allows the coordinate transformation from the sensor frame S to the inertial frame I, expressed as:

$$R = \begin{bmatrix} cos\alpha cos\beta & cos\alpha sin\beta sin\gamma - sin\alpha cos\gamma & cos\alpha sin\beta cos\gamma + sin\alpha sin\gamma \\ sin\alpha cos\beta & sin\alpha sin\beta sin\gamma + cos\alpha cos\gamma & sin\alpha sin\beta cos\gamma - cos\alpha sin\gamma \\ -sin\beta & cos\beta sin\gamma & cos\beta cos\gamma \end{bmatrix} \quad (1)$$

where α is the yaw angle, β is the pitch angle, and γ is the roll angle. As we can note, the vector ${}^{S}Z$ (i.e., the last row of the matrix R) in (1) is expressed in terms of γ and β. Hence, knowing ${}^{S}Z$, tilt angles can be calculated:

$$\gamma = \tan^{-1}\left(\frac{{}^{S}Z_2}{{}^{S}Z_3}\right) \text{ and } \beta = \tan^{-1}\left(\frac{{}^{S}Z_1}{{}^{S}Z_2/sin\gamma}\right) \quad (2)$$

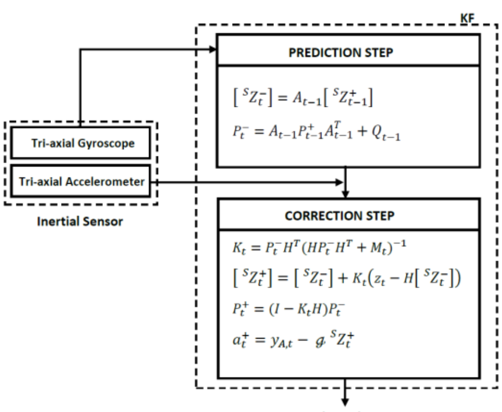

Figure 2. Chart of the estimation of orientation by fusion sensors with Kalman Filters (KF).

The KF is defined by the process model:

$$\mathrm{x}_t = A_{t-1}\mathrm{x}_{t-1} + w_{t-1} \quad (3)$$

and the measurement model.

$$z_t = H\mathrm{x}_t + v_t \quad (4)$$

Where x_t in (3) is the state vector, defined by the purpose of the KF as $\mathrm{x}_t = \left[{}^{S}Z_t^-\right]^T$, A is the state transition matrix, and w is the white Gaussian process noise. In (4), z_t is the measurement vector, H is the observation matrix, and v is the white Gaussian measurement noise.

As explained, the orientation estimation is calculated by the mathematical integration of the gyroscope signals. Hence, following the deduction reported by Lee et al. [12], the process model can be expressed as:

$${}^{S}Z_{\cdot t} = \left(I - \Delta t\, \tilde{y}_{G,t-1}\right) {}^{S}Z_{\cdot t-1} + \Delta t\left(- {}^{S}\tilde{Z}_{\cdot t-1}\right)n_G \quad (5)$$

where n_G is the gyroscope measurements noise that is assumed white Gaussian with zero mean.

Thus, from (5), the transition matrix A_{t-1} and the process noise w_{t-1} can be defined as:

$$A_{t-1} = I - \Delta t\, \tilde{y}_{G,t-1} \quad (6)$$

$$w_{t-1} = \Delta t\left(- {}^{S}\tilde{Z}_{\cdot t-1}\right)n_G \quad (7)$$

Now, the process noise covariance matrix Q_{t-1} defined by $E[w_{t-1}w_{t-1}^T]$, can be redefined using (7) as:

$$Q_{t-1} = -\Delta t^2\, {}^{S}\tilde{Z}_{\cdot t-1}\, \Sigma_G\, {}^{S}\tilde{Z}_{\cdot t-1} \quad (8)$$

where Σ_G, defined as $E[n_G n_G^T]$, is the covariance matrix of the gyroscope measurements noise and is established as a 3x3 diagonal matrix with the gyroscope noise variance of x, y, z axes in the main diagonal:

$$\Sigma_G = \mathrm{diag}(\sigma_{Gx}^2, \sigma_{Gy}^2, \sigma_{Gz}^2) \quad (9)$$

The measurement model is based on the accelerometer's measurements since they give the spatial reference to correct the estimation error in the process model. Therefore, the external acceleration is subtracted from the accelerometer measurements to ensure the gravity vector's correct reference. The model of the external acceleration can be defined as:

$$.{}^{S}a_t = .{}^{S}a_t^- - .{}^{S}a_{\varepsilon,t}^- \quad (10)$$

In (10) $.{}^{S}a_t^-$ is the predicted (a priori) external acceleration defined as $C_a.{}^{S}a_{t-1}^+$, where C_a is a dimensionless mixing constant in the range [0, 1]. And $.{}^{S}a_{\varepsilon,t}^-$ is the error of the predicted acceleration.

Hence, the measurement model can be established by follows (see details in [12]):

$$Y_{A,t} - C_a.{}^{S}a_{t-1}^+ = g\, {}^{S}\tilde{Z}_{\cdot t} - .{}^{S}a_{\varepsilon,t}^- + n_A \quad (11)$$

where n_A is the accelerometer measurements noise that is assumed white Gaussian with zero mean.

And so, the measurement vector z_t, the observation matrix H and the measurement noise v_t are:

$$z_t = Y_{A,t} - C_a.^S a_{t-1}^+ \quad (12)$$

$$H = gI \quad (13)$$

$$v_t = -.^S a_{\varepsilon,t}^- + n_A \quad (14)$$

The measurement noise covariance matrix M_t, defined by $E[v_t v_t^T]$, is expressed as:

$$M_t = \Sigma_{acc} + \Sigma_A \quad (15)$$

where Σ_{acc} is the covariance matrix of the acceleration model error defined as $3^{-1} Ca^2 \|.^S a_{t-1}^+\| .^2 I$ and Σ_A is the covariance matrix of the accelerometers measurements noise defined as the 3x3 diagonal matrix diag$(\sigma_{Ax}^2, \sigma_{Ay}^2, \sigma_{Az}^2)$.

Finally, once $\left[{}^S Z_t^-\right]^T$ is estimated, the external acceleration a_t^+ can be calculated by:

$$a_t^+ = y_{A,t} - g\, {}^S Z_t^{\;+} \quad (16)$$

Figure 2 illustrates the structure of the proposed algorithm [12][13].

B. Multi-IMU System Design

A printed circuit board containing a commercial inertial measurement unit (Invensense MPU-9250) was designed with dimensions small enough, of 14 x 12 mm, to monitor patients' subtle movements without limiting their mobility. The system's architecture consists of a string of 6 sensors, which allows it to be ergonomically placed along the patient's spine with hypoallergenic double-sided tape (Fig. 3a), enabling more precise assessment than current available IMG-based systems [14]. The first sensor was attached over the first thoracic vertebra at the patient's neck. And, the last sensor of the string is attached over the fifth lumbar vertebra, leaving an equidistant separation between the sensors.

The sensors' signals were recollected through a compact and portable wireless control unit, mounted in the patient's back through a harness. The control unit consists of a central digital signal processor (DSP), interfaced with the sensors through an eight-channel fast multiplexor (TCA9548A) for I2C communication. In this way, the DSP (Teensy 3.2) collects the raw data from the sensors in real-time and sends the information to a computer through a Bluetooth wireless communication protocol (HC-05 version 3.0). A software desktop application was implemented to estimate the orientation of each sensor, using a set of six instances of the presented Kalman filter algorithm, with each instance specifically associated and calibrated per sensor [15] (Fig 4).

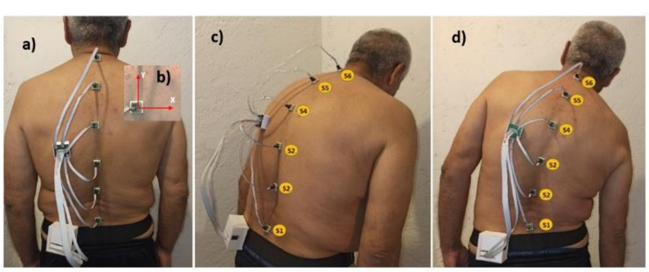

Figure 3. a) Embodiment of the proposed system; b) Frame reference of the sensors, with Z-axis is out of the image. The movements considered in the experimental study. c) Frontal flexion; d) Lateral flexion.

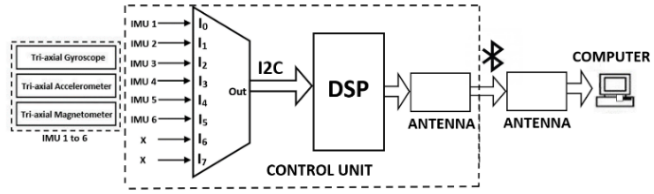

Figure 4. The architecture of the Control Unit of the proposed portable and wireless system.

The complete solution provides kinematic pose estimation of patient articulations related to spinal mobility at a frame rate of 100 Hz per sensor, which is an adequate sampling rate for clinical evaluations.

III. Preliminary Tests with Patients

A. Recruitment

With the aim to evaluate the system's functionality, two AS patients (male; age 45, 49 years; mass 70, 80 kg; height 1.65, 1.70 m) at the Rheumatism Unit Service at the General Hospital of Mexico "Dr. Eduardo Liceaga" were recruited and invited to participate in the preliminary tests. The inclusion criteria were to be an AS patient diagnosed without several restricted hip motility or spinal deformity. The participants signed the informed consent, and the Local Ethics Committee of the Hospital approved the study (protocol code DI/03/17/471).

B. Evaluation Tests

The patients were asked to perform two spinal movements from the routine clinical tests (Fig 3c-d): a series of four maximum frontal hip flexion, known as the modified Schober test; and four lumbar lateral flexions of the spine to the left and right sides. These two movements are part of the BASMI.

IV. Results

Two movements of the BASMI were tested, frontal hip flexion (the Modified Schober test) and lumbar lateral flexion. Figure 5 shows the measured angles and the kinematic chain of the two patients making anterior hip flexion. Figure 5A presents the estimated trajectory of pitch angle (x-axis rotation) of the spine sensors, expressing the ranges of motion (RoM) of the anterior hip flexion. Each

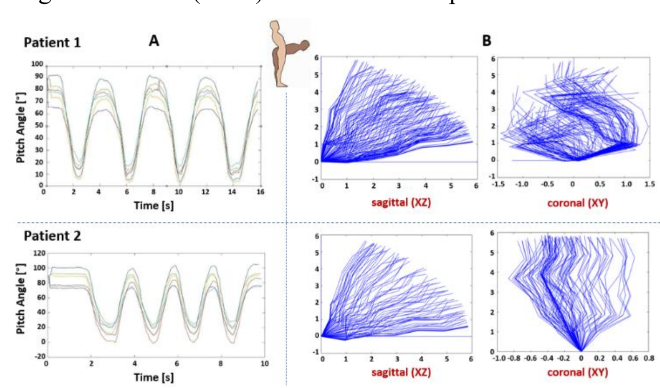

Figure 5. Anterior hip flexion movement of two AS patients; A) estimated trajectory of the pitch angle of the spine sensors B) kinematic chain of the spine segments in the sagittal and coronal planes.

signal describes the orientation of a single IMU. The difference in amplitude of the signals can be observed due to the patient's spine's inclination; the farther the IMU is placed from the lumbosacral joint (bottom reference at the spine in the Schober test), the greater amplitude of the RoM. Figure 5B, shows the kinematic chain of the spine segments. The plots' ordinate axis ranges from 0 to 6, representing the six kinematic segments into which the spine is "divided" by the sensors. The anterior hip flexion movements dominate in the sagittal plane. Still, it is possible to see some coronal plane movement, showing compensation due to the AS, and oscillation in patient 1 (abscissa axis).

Figure 6A presents the roll angle curves (z-axis rotation) of each IMU, describing the lumbar lateral flexion movement; similarly, each signal describes the same exercise with different amplitudes. In this case, the RoM curves' differences can be observed for the right lateral flexion versus the left lateral flexion due to the patient's clinical condition. Figure 6B shows the kinematic chain for the lateral flexion. These movements dominate in the coronal plane. However, it is possible to see noticeable differences between patients in the sagittal plane, which illustrates that the system can provide discriminant metrics and motion information. This aspect will be studied as the next step of this research.

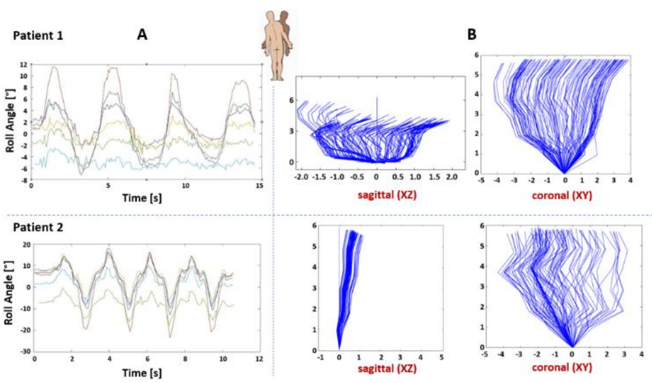

Figure 6. Lumbar lateral flexion movement of two AS patients; A) estimated trajectory of the roll angle of the spine sensors B) kinematic chain of the spine segments in the sagittal and coronal planes.

V. CONCLUSION

We demonstrated the feasibility of using the proposed multi-inertial sensor system in patients with AS before conducting extended clinical tests for evaluating the system's accuracy, repeatability, and sensibility to changes. Based on the tests carried out, it is observed that the system is capable of detecting subtle movements undetectable by traditional methods, presenting advantages over them. The BASMI index only considers movements of the patient's spine but is not sensitive to possible erratic movements due to the rigidity and inflammation of the axial musculoskeletal system.

The number of IMUs (i.e., six) allows obtaining more objective information of the patients' spine motion condition, since it is important to consider the thoracic spine, which is also affected by the disease; unlike the reported works [10][11]. Therefore, it is expected that can provide greater sensitivity to changes in the patient's mobility. As future work, a controlled clinical study with more patients with AS will be carried out to validate the system and figure out better movement characteristics in rheumatic patients than traditional methods.

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