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A simple test to assess the static and dynamic accuracy of an inertial sensors system for human movement analysis

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Abstract—**In the present study we introduced a simple test to assess the orientation error of an inertial sensors system for human movement analysis, both in static and dynamic conditions. In particular, the test was intended to quantify the sensitivity of the orientation error to direction and velocity of rotation. The test procedure was performed on a 5 MT9B sensors Xsens acquisition system, and revealed that the system orientation error, expressed by Euler angles decomposition, was sensitive both to direction and to velocity, being higher for fast movements: for mean rotation velocities of 180°/s and 360°/s, the worst case orientation error was 5.4° and 11.6°, respectively. The test can be suggested therefore as a useful tool to verify the user specific system accuracy without requiring any special equipment. In addition, the test provides further error information concerning direction and velocity of the movement which are not supplied by the producer, since they depend on the specific field of application.**

I. INTRODUCTION

Technology advances in the design of miniaturized, low-cost and low-power sensors have recently enabled their use for a wide variety of biomedical applications. In particular, miniaturized inertial sensors, such as MEMS accelerometers and gyroscopes, are strategic for human movement analysis, because of their characteristic of portability and the useful kinematic information they provide. These characteristics make such sensors particularly appropriate when unobtrusiveness and ubiquitous availability are critical requirements, as in movement functional evaluation (both in small and outdoor environments) and in daily-life activities monitoring. The potential of such technology for movement analysis is attracting large interest in the scientific community and its use has become increasingly widespread [1-5]. However such approach still needs to be fully exploited for a correct and accurate use in movement analysis. For example discrimination between static and dynamic accelerations was proved to be a critical issue [6;7], and the use of accelerometers alone for the reconstruction of the full body joint kinematics was found to be insufficient [8].

To explore the potentials of acquisition systems based on inertial sensors, and to move toward their systematic use, it is essential to define specific acquisition protocols that depend on the body segments under investigation and on the particular purpose of the movement assessment.

In the present study we considered a commercial system, recently proposed on the market (Xbus Kit based on MT9B sensors, Xsens Technologies, NL), that integrates 3 different kinds of sensor in each sensing unit: a three-axes accelerometer, a three-axes gyroscope and a magnetometer. Each sensing unit, hereafter referred to as MT9B, allows the estimation of its absolute orientation with respect to an earth-based global reference frame.

In order to define a motion analysis protocol based on the Xsens system, it is important to assess the accuracy in the estimation of the orientation of a body segment on which the sensing units are mounted. Indeed, the information provided by Xsens MT9B User Manual to this regard are quite generic: each MT9B sensor static accuracy is described as less than 1° and the dynamic accuracy is described as 3° of RMS. In addition, a note specifies that the error in dynamic condition "may depend on the motion". No information about the concomitant use of more than one sensing unit is provided.

The aim of the present study was to design and perform a simple test, in static and dynamic conditions, to assess the orientation error of an inertial sensors system for human movement analysis. In particular the test was conceived to assess the sensitivity of the orientation error to the specific characteristics of the movement, both in terms of movement direction and velocity. In the present study the test was implemented to verify the MT9B Xsens accuracy.

II. METHODS

A. *Data acquisition system*

The Xbus Kit employed in the present study comprises 5 MT9B inertial sensing units. Each MT9B includes a three-axes accelerometer, a three-axes gyroscope and a magnetometer, all assembled within a single small plastic

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case (39x54x28 mm, 38g of weight). A 3D orthogonal reference frame is associated with each MT9B, well aligned along the sides of the sensor case (errors <3°).

Within each sensing unit, the information provided by the accelerometer, gyroscope and magnetometer are integrated by means of a Kalman filter, allowing the estimation of the absolute orientation of the unit local reference frame with respect to an earth-based reference system. The measurement of gravity acceleration (by means of the accelerometer) and magnetic north (by means of the magnetometer) compensates for otherwise unlimited increasing errors from the integration of rate of turn data. The magnetometer, in particular, allows associating the relative orientation coming from two inertial sensors, to a global reference system. The orientation in the 3D space of each unit may be provided by Xsens in a wide variety of formats. The most significant for applications in biomechanics is the rotation matrix, which relates the local with respect to the global orientation.

The simultaneous use of the 5 MT9B units is allowed by the Xbus Master, to which each MT9B communicates by a wired connection. The Xbus Master can communicate with the computer dedicated to the data acquisition, both via a wired or a wireless connection (Bluetooth protocol). In the present study the wireless connection was chosen, to allow unconstrained movements during the test. The acquisition frequency of each sensing unit was set to 100 Hz.

B. Test procedure

The test was performed in a typical motion analysis laboratory (with desks, metallic cabinets, force platforms, computers etc…), but the sensors were at least 2m away from any ferromagnetic object in the laboratory. All mobile phones were switched off to avoid any electromagnetic field interference. The MT9Bs were wormed up for 15 minutes before use, and the electromagnetic disturbances compensating filters were turned off, as recommended in the Xsens Manual for regular acquisitions.

Four sensors were attached on a rigid plate of thermo-formable (at 150-180°C) plastic for prosthesis, 9 mm thick. The 4 sensing units were firmly glued on the rigid plate, parallel to each other and to the plate boundaries (Figure 1).

A set up including 4 out of the 5 available sensors was considered for the test, both for simplicity, and because 4 sensors are sufficient in an experimental set-up to study upper arm kinematic. Indeed such application is the main we mean to develop with the Xsens data acquisition system [9].

The test procedure consisted of a static and dynamic session. The static session just required a 10 second acquisition, with the plate still on a table. The dynamic session required three different rotations of the plate, at two different velocities, resulting in six different conditions.

The three different rotations were executed by spinning manually the plate (six cyclical movements of ±180°) around the x, y and z axes of the sensors (represented in Figure 1). Each rotation, hereafter referred to as Rot*x*, Rot*y*, Rot*z*, was performed with a mean velocity of 180°/s and of 360°/s. Each velocity was maintained thanks to the use of a metronome.

For each condition 3 repetitions were performed and acquired, thus obtaining the following set of data:

$\mathrm{Rot}x_i^{180}$ $\mathrm{Rot}x_i^{360}$ i=1: 3
$\mathrm{Rot}y_i^{180}$ $\mathrm{Rot}y_i^{360}$ i=1: 3
$\mathrm{Rot}z_i^{180}$ $\mathrm{Rot}z_i^{360}$ i=1: 3

All acquisitions were managed with custom made software based on MATLAB, which automatically computed the relative orientation of all the six possible sensors couples formable out the four sensors used.

C. Measure of the orientation error

The relative orientation of each sensor with respect to each other was computed and expressed in terms of Euler angles (α,β,γ). For Rot*x*, the rotation sequence for Euler angles computation was xzy, for Rot*y* was yxz, and for Rot*z* was zxy. In this way the first angle α always corresponded to the direction around which the rotation was performed.

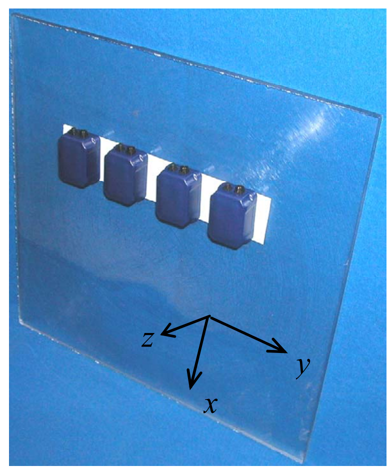

Fig. 1. MT9 sensing units set up for the test execution.

Due to the rigidity constraint imposed by the plate on the sensors, an error-free system would measure a constant angular displacement for each sensor with respect to the others, independently from the motion applied to the plate. The Xsens static and dynamic accuracy can be therefore assessed measuring the differences of the estimated relative kinematics from this ideal behaviour. For all tasks (including the static one) and sensors couples, the range of the displacement of each Euler angle component was measured and it was considered as the measure of the orientation error. All possible paired combinations of the four sensors resulted in six couples, and hence in six range values for each angle, for each trial. Since we were interested to the overall behaviour of the 4 sensors, we grouped the information regarding the same angle, even if from different sensors pairing and from the three repeated tasks. Each condition (a given rotation and given velocity) was thus represented by 18 samples of the error measure for each Euler angle.

D. *Statistical analysis*

After verifying the normality of the data [10], the dependence of the orientation error on velocity (180°/s, 360°/s), rotation direction (Rot*x*, Rot*y*, Rot*z*) and on the specific angle (α,β,γ) was evaluated by a 3-factors ANOVA. Comparison tests for factor interactions were performed by the Tukey-Kramer test. All the statistical analyses were performed with the software NCSS [10].

III. Results

For the static task, the worst case static error was 0.32°, far below the declared values for a single sensor.

Results from the dynamic tests revealed that the error measure depended on the direction ($p<<0.001$) and on the velocity ($p<<0.001$) of the rotational movement, as shown in Figure 2, where the mean values and SD of the ranges of Euler angles are represented.

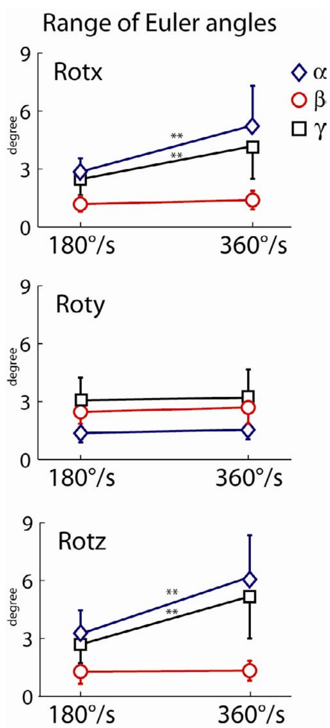

Fig. 2 Orientation error (range of the Euler angles) for the three rotational directions and for the two different velocities. Mean values and SD (asymmetric for graphical reasons) are represented. ***: p< 0.05*

Results regarding Rot*x* and Rot*z* presented a different behaviour than those regarding Rot*y* ($p<0.05$), for what concerns influence of velocity, and distribution of the orientation error among the Euler angles. In fact, Rot*y* resulted completely immune from velocity influence, while for Rot*x* and Rot*z* orientation error significantly increased with velocity ($p<0.05$) for two out of three angles, α and γ, associated with the axis of rotation and with the *y* axis, respectively.

In both velocity conditions, when the rotation was performed around *x* or *z*, the orientation error distribution was primarily concentrated on α (i.e. around the axis of rotation) and γ, angles that resulted significantly different from β ($p<0.01$). On the contrary, when the rotation was performed around *y*, the results highlighted a less amount of orientation error ($p<0.05$) along the axis of rotation (α), than for β and γ.

The worst case orientation errors occurred for rotation around z and in particular were α =5.6° for slow rotation, α=11.6° for fast rotation.

IV. Discussion

The test we proposed for the assessment of the accuracy of inertial sensors may be suggested as a useful tool for the understanding of the orientation errors, intrinsic in a data acquisition system when applied to human motion analysis, and to periodically test the performances of the acquisition system. In particular the test is able to identify the sensitivity to velocity and direction of the movement, when implemented for the MT9B XSens data acquisition system.

The test procedure was conceived to be easily replicable by any user without any ad-hoc devices, since it just requires the acquisition system itself as along as a rigid plastic plate. The environment in which the test was performed was not completely free from ferromagnetic material, reflecting a typical motion analysis laboratory.

Since the test prescribed to manually rotate the plate, the rotations may have not been perfectly single-axial (even if a plate support was used in the execution of the movement), but this procedure has the great benefit of causing the velocity and acceleration profiles to reflect those typical of a human movement.

The results presented in the study are consisted with the accuracy information provided in the Xsens User Manual, since a reported RMS of 3° corresponds to a range of 12° (±2RMS) to include over the 95% of all possible occurrences of the same measure. However, the proposed test procedure provides further information that specifically regards direction and velocity of the movement, information otherwise not available by the user.

Evaluation of sensitivity to direction of movement highlighted that for rotations around x and z, the orientation errors are largest around the axis of rotation. Further analyses on the orientation data were performed both using other Euler conventions (xyz for Rot*x*, yzx for Rot*y* and zyx for Rot*z*) and using the Attitude Vector convention [11] to verify the independence of results on the orientation decomposition. The analyses confirmed the results already presented in this study.

In addition our results suggest that slow motions should be performed in order to obtain best results and that the *y* axis appears more stable with respect to velocity changes. Assuming slow movements, errors in the reconstruction of the inter-joint kinematics should be expected to be on the average about 3°, with worst errors of about 6°. Therefore MT9B Xsens still appears to be inferior, in terms of orientation accuracy than optical movement analysis systems based on infrared cameras, as characterized by Cappozzo et al. [12]. This drawback is far overcome, in the authors' opinion, by the advantages of the inertial sensors system, being it cheaper, portable and easily wearable.

Further developments of the study will include specific tests and data analyses to detect possible anomalies of a specific sensor among the entire set used in an experimental set-up, to suggest caution in the use a specific sensor and allow the appropriate use of the data acquisition system.

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