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Experimental evaluation of accuracy and repeatability of a novel body-to-sensor calibration procedure for inertial sensor-based gait analysis

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ABSTRACT

This paper describes a novel functional body-to-sensor calibration procedure for inertial sensor-based gait analysis. The procedure is designed to be easily and autonomously performable by the subject, without the need for precise sensor positioning, or the performance of specific movements. The procedure consists in measuring the vertical axis during two static positions, and is not affected by magnetic field distortion. The procedure has been validated on ten healthy subjects using an optoelectronic system to measure the actual body-to-sensor rotation matrices.

The effects of different sensor positions on each body segment, or different levels of subject inclination during the second static position of the procedure, resulted unnoticeable. The procedure showed accuracy and repeatability values less than 4° for each angle except for the ankle int–external rotation (9.7°, 7.2°). The results demonstrate the validity of the procedure, since they are comparable with those reported for the most-adopted protocols in gait analysis.

1. Introduction

The recent technological advances in MEMS caused a renewed interest in the use of Inertial Measurement Units (IMUs) to perform effective biomechanical studies such as fall detection, gesture recognition, and locomotion analysis in healthy subjects and in patients with pathology [1–9]. IMUs are generally referred to as a combination of linear accelerometers and gyroscopes – from a minimal setup to measure 3D motion to redundant setups [10–12] – and when the cluster also includes magnetometers, they are referred as MIMUs. From the comparative examination of IMU/MIMUs with optoelectronic systems (OSs), which are considered the golden standard for human motion analysis, it emerges that the IMU/MIMUs have the following general advantages: they do not require a dedicated laboratory, they permit a wider workspace, and they are low cost devices [13]. Their main drawbacks are as follows. Firstly, IMU/MIMUs are affected by intrinsic bias and inaccuracy due to the drift related to the integration of gyroscope data; actually, this produces large inaccuracy in the estimation of angular rotations and still greater effects in the evaluation of linear velocities and displacements [14,15]. Secondly, MIMUs are prone to disturbance effects induced by the presence of ferromagnetic materials around

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the sensors [16–20]. Nevertheless, the main strength of IMU/MIMUs is represented by data fusion algorithms, designed to reduce these errors under values acceptable for human motion analysis. So far several algorithms have been proposed [15,19,21–24].

An additional issue related to IMU/MIMU-based systems in the study of human motion is the alignment of sensor axes with anatomical ones. In fact, due to their inaccessibility, the problem is solved performing a calibration procedure for the assessment of the relative rotation between sensor and body segment frames. Picerno et al. [25] proposed an *ad hoc* tool instrumented with a MIMU, nominally identical to the sensors placed on the subject, for the evaluation of the body-to-sensor rotation matrices for the lower limb. The tool was designed to touch some anatomical landmarks, while the sensor placed on the tool measured the orientation of the vector connecting the landmarks expressed in its reference frame. This intermediate step led to the computation of each body-to-sensor matrix, under the assumption that both the pointer MIMU and the one placed on the body segment had the same reference frame.

From a survey of the literature, it emerges that most of the calibration procedures proposed were based on a functional approach for the kinematic evaluation of upper [26,27] and lower limbs [28,29]. In the functional approach, the estimation of anatomical axes is carried-out measuring the components of the gravity acceleration vector in predefined segment orientations, and/or the components of the angular velocity vector between two consecutive body segments during joint rotations, often performed with the help of an operator. The mentioned vectors measured in the sensor frame were assumed to be parallel to the anatomical axes during static positions or movements. Focusing on lower limb analysis, O'Donovan et al. [28] defined a two-phase functional calibration procedure. Anatomical axes, for ankle kinematics evaluation, were estimated in the sensor frame during two body segment rotations: the first around the longitudinal axis of tibia and the second around the knee flexion axis. However, accurately performing a whole-body rotation while maintaining the longitudinal axis of tibia parallel to the vertical axis may be difficult, especially for patients. In order to perform the knee kinematics evaluation, in fact, Favre et al. [29] let an examiner move the shank of the subject during the calibration procedure to estimate anatomical axes of tibia in the corresponding sensor frame. Cutti et al. [30,31], introduced the "Outwalk" protocol for MIMU sensors placement and a functional calibration procedure, in order to make fast and comfortable the use of MIMUs for joint kinematics evaluation. The protocol is the most complete in terms of segments involved and procedure description, as well as the easiest to perform. It provides indications for MIMU positioning and anatomical frame definition of 7 segments modeled lower limb plus thorax, during standing position, and a knee flexion movement to compute the mean knee flexion–extension axis. However, the protocol requires a precise positioning for some sensors, positioned at the pelvis, thorax or shank. The effects of mounting the sensors with a slightly different orientation or position may cause a further degradation of experimental data with an increase of standard deviation both in retesting the same subject and in examining different individuals.

The previously mentioned calibration procedures require: (i) the presence of an expert operator to help the subject in performing specific movements or to mount MIMUs in well-defined positions; or, finally, (ii) to handle additional tools. These requirements actually restrict the use of IMU/MIMU in day-to-day life. Instead, the independent use of the procedure by the subject represents a relevant feature in the context of motion analysis sessions conducted outside of a clinical environment and during daily activity as also reported by previous studies [32–34]. In addition, most of the proposed calibration procedures described above allow the computation of the calibration matrix of a sensor by means of data provided by one or more sensors placed on other body segments. According to Picerno et al. [35], due to local magnetic field distortions, sensor data may be referred not to the same ground frame, compromising the reliability of joint kinematics. Thus, calibration procedures that allow the computation of the body-to-sensor rotation matrix for each sensor independently should be preferred.

It is also worth noting that none of the proposed procedures used the anatomical frame definition introduced by Wu et al. [36], generally accepted as a standard in biomechanics. Actually, the assessment of the orientation of axes defined in their work is not feasible with a functional procedure. This represents a relevant limitation in comparing results of motion analyses conducted via IMU/MIMU and OS.

Taking into account the previously mentioned findings, the aim of the present work is the proposal of a novel two-phase functional calibration procedure for lower-limb kinematics evaluation, designed to obtain the body-to-sensor alignment independently for each sensor and without requiring a skilled experimenter. Then, we intend to evaluate the accuracy and the repeatability of the proposed calibration procedure performed with a commercially available MIMU system relative to the calibration obtained using an OS. In particular, we plan to investigate whether the effects of the calibration repeatability on the measurement of hip, knee and ankle angles during gait were acceptable by gait analysis practices. Additionally, we intend to evaluate the difference between the joint kinematics obtained with the anatomical axes definition introduced for the calibration, and the one obtained with the standard Joint Coordinate System (JCS) definition proposed by Wu et al. [36] and adopted by International Society of Biomechanics (ISB).

2. Matherial and methods

2.1. Lower-limb joint kinematics

The estimation of joint angles consists in the evaluation of joint rotations between two body segments and, therefore, in the calculation of joint rotation matrices. The rotation matrix ${}^{b_i}\mathbf{R}_{b_j}$ between two coordinate systems (CS_{b_i} and CS_{b_j}) relative to the body frames b_i and b_j can be computed as follows: