3D joint rotation measurement using MEMs inertial sensors: Application to the knee joint

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Abstract—**This study investigated a functional calibration method to define the Cartesian bone-embedded anatomical frame necessary to calculate 3D joint angles. This method was combined with an inertial ambulatory system and applied to the measurement of 3D knee joint angles during gait. This combination was compared to a magnetic tracker system associated with a functional and postural calibration method. The measurement errors due to the shank's soft tissues were also evaluated by the use of a harness. The combinations of the inertial acquisition system with the functional calibration method show good results. The errors obtained with different attachment methods did not show significant differences. The proposed combination constitutes a very promising tool for clinical evaluations.**

Keywords-component; 3D angle; MEMS based system; calibration method; skin movement.

I. INTRODUCTION

The measurement of three-dimensional (3D) joint rotations is a core part in biomechanics and constitutes a very promising tool for orthopedic evaluation [1]. Although, the standard motion capture systems, based on optoelectronic, magnetic or ultrasonic technologies, provide valuable information regarding joint orientations; they are costly and needs a dedicated laboratory and a well trained staff. Moreover, their use for ambulatory or long time measurements are usually impossible and their use in clinical routine evaluations are very limited.

Recent progress in microelectromechanical system (MEMs), allows the design of small and light sensory units, which can be fixed on body segments without interfering with the movement. These units can be battery-powered, and offer a simple way for ambulatory monitoring [2]. Due to their low power consumption and their high memory capacity available nowadays, these units can be used for long time recording [3]. Sensor configuration depends on the application: for 3D measurements, triaxial gyroscopes and triaxial accelerometers are often fused [4, 5]. In addition, to avoid long-term drift, some authors also considered triaxial magnetometers [6, 7].

The information given by inertial systems, such as for standard laboratory ones, is the orientation of the body fixed units frame respectively to a reference frame. So, if two of those units are fixed on two body segments bounded by a joint, the 3D rotation of the joint can be calculated based on the orientations of the two units. In order to describe the kinematics of the joint by three angles, a mathematical model must be adopted. The International Society of Biomechanics (ISB) recommended the Joint Coordinate System (JCS) as proposed by Grood and Suntay [8-10]. This model calculates the three angles (and translations) based on the orientation (and position) of the two Cartesian bone-embedded anatomical frame (BAF). In the paper of Grood and Suntay, an example of BAF was proposed for the knee joint. In 1995, Cappozzo et al. proposed a definition for the BAF of the pelvis and the lower limb bones [11]. As Grood and Suntay, the BAF described by Cappozzo et al. were constructed based on anatomic landmarks. Others authors suggested functional calibration procedure, where the BAF were defined through the execution of specific movements [12], or semi-functional procedure, where the BAF were defined by localization of anatomic landmarks and execution of movements [13]. More recently, Hagemeister et al. proposed a functional and postural calibration method [14]. But all these methods were used with laboratory tracking systems measuring position and orientation, and currently no MEMs based device allows the measurement of position.

Whatever the selected motion capture system, the orientation measured with sensors or markers on the skin do not reflect exactly the bone's orientation. Measurement artefacts due to both active and passive soft tissues will modify the transformation between the sensor frame and the BAF. This could severely corrupt the 3D motion analysis [15]. Although, some improvements were proposed for systems using markers glued on the skin [15-16], these solutions can not be applied to inertial sensors.

The purpose of this study was twofold: first, to propose a new calibration procedure for knee joint's BAF definition based on MEMS sensors; secondly, to evaluate the effect of skin artefacts using an orthoplastic exoskeleton attachment system (harness) [17] which can fit well with MEMS based recording system. The errors when the 3D knee joint angles are calculated with MEMS sensors fixed on the harness or directly on the skin were evaluated.

II. MATERIALS AND METHODS

A. Inertial measuring system and clibration procedure

The system is composed of two small sensory units, each including a 3D gyroscope and a 3D accelerometer, connected to a portable data-logger (Physilog®, BioAGM, CH) (see Fig.1). The data were recorded with a sampling frequency of 240Hz. The orientations of the two units' frame respectively to a common global frame were calculated according to Favre et al. [5].

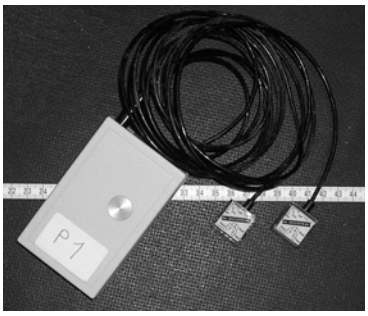

Figure 1. A Physilog® data-logger and two units composed of 3D gyroscope and 3D accelerometer.

The alignment of the units' frame with the BAFs required by the JCS was done by a functional calibration in three steps. First, the angular velocity of the shank was measured by the strapped-down gyroscope while the subject was sitting and performing passive knee flexion-extension without moving the thigh (Fig. 2a). The X axis of the shank's BAF was defined as the mean rotation axis calculated with the angular velocity. Secondly, in sitting position and without moving the thigh, the subject performed passive knee abduction-adduction movements with the help of an operator (Fig. 2b). The rotation axis calculated with this angular velocity defined the mean Y' axis. In order to obtain a Cartesian XYZ BAF, the Z axis was defined as the normal to (X, Y') plane and finally the Y axis was defined as the normal to (Z, X) plane.

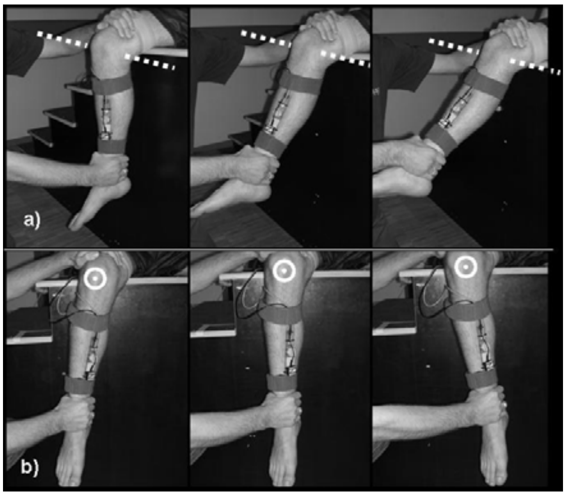

Figure 2. Passive movements used to calibrate the inertial system.

In the third step of the calibration, the subject was asked to stand in an upright position. In order to get the three knee angles equal to zero for this position, the XYZ BAF of the thigh was defined collinear with the shank's BAF while the subject was standing still.

B. Reference measuring system

The reference system consisted of both parts (thigh and shank) of the harness [17] combined with a magnetic tracking system (Liberty®, Polhemus, USA) (Fig. 3). The data were recorded with a sampling frequency of 240 Hz. The 3D knee angles were calculated based on the calibration method using the same JCS as described in Hagemeister and al [14].

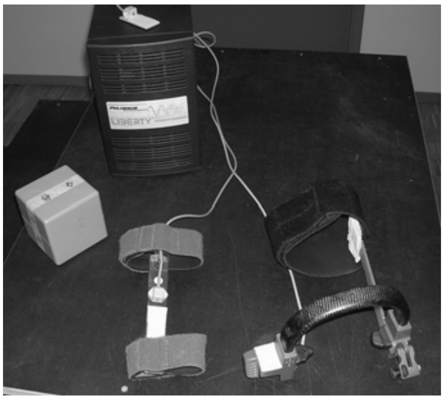

Figure 3. A Liberty® magnetic tracking system fixed on the harness.

C. Experimental protocol

Four healthy men (26 ± 2 years old) were included in this study. They were asked to walk two times on seven meters along a path at self selected speed. For the first trial, the inertial system was fixed on the harness whereas during the second trial, the thigh's inertial unit was fixed directly on the skin by a silicone strap. Both systems were calibrated before each trial. The 3D knee angles obtained through the proposed inertial system were compared with those of the reference system for two different values. First, the gait cycles were delimited according to [18], and the mean range of motion (ROM) was calculated for each system based on all subjects in each trial. Secondly, the mean and standard deviation of the error between inertial and reference systems were calculated separately for each trial through all subjects by considering the continuous time 3D knee angles.

III. RESULTS

Fig. 4 displays the angular velocities of the shank and the associated BAF obtained during the functional calibration as shown in Fig.2 for a typical subject. Table I depicts the mean gait cycles ROMs. When the inertial unit was rigidly fixed on the harness the ROM in flexion were equal to respectively 51.5 and 52.5 degrees. The adduction/abduction movement ranged from 10 to 10.5 degrees, and the internal/external rotation varied from 14 to 13 degrees. Table II shows the mean (μ) and standard deviation (SD) of the errors for the eight trials. Fig. 5 illustrates the 3D knee angles for a typical walk (subject 3) while the inertial system was fixed on the harness (Fig.5a) and on the skin (Fig.5b).

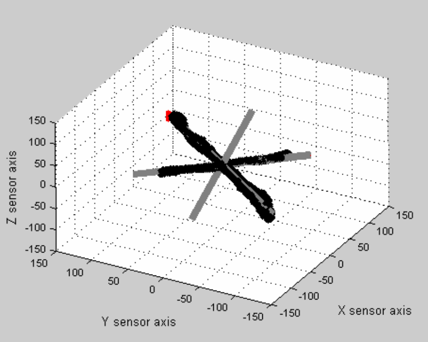

Figure 4. A typical shank's BAF dfined by passive movements of fig.2. The black lines correspond to the angular velocities (°/s) and the gray lines to the XYZ BAF associated axes.

TABLE I. MEAN ROMS

Inertial unit fixed on	Flexion/ extension		Adduction/ abduction		Internal/external rotation	
	MEMS	***REF***	***MEMS***	***REF***	***MEMS***	***REF***
Harness	51.5	52.5	10	10.5	14	13
Skin	48.8	49.3	10.3	11.5	12.8	12.3

MEMS correspond to the inertial system and REF to the reference system.

The ROMs are expressed in degree

TABLE II. 3D KNEE ANGLES ERRORS

Subject		Flexion/ extension		Adduction/ abduction		Internal/external rotation	
		μ	*SD*	μ	*SD*	μ	*SD*
On the harness	**1**	15	1.8	1.8	2.1	1.7	2.0
	2	1.3	2.2	1.9	1.5	2.1	1.1
	3	3	1.5	2.1	2.5	1.2	1.3
	4	6.2	1.3	11	2.1	2.3	2.3
On the skin	**1**	12	2.2	3.3	1.4	3.7	3.1
	2	3	1.8	1.0	1.3	4.2	1.7
	3	1.3	1.4	4.4	2.4	2.9	2.0
	4	12	2.2	3.3	1.4	3.7	3.1

μ and SD are expressed in degree

IV. DISCUSSION

The mean ROMs (Table I) obtained through the inertial system were very close to those of the reference system, with a maximum difference of 1°. For the ROMs, the results obtained with the inertial shank's unit fixed on the harness or on the skin were very close. When comparing the ROMs of the first trial with the second, almost same amplitudes could be noticed for both systems.

The mean errors obtained for 3D knee angles (Table II), varied between 1.7° and 15° for the inertial unit fixed on the harness and between 1.3° and 12° for skin attachment. The corresponding SD errors were between 1.1° and 2.5° and between 1.3° and 3.1°. These errors are attributed probably to different calibration methods used in both systems. The small SD errors reflect close definition of the axes representing the JCS. The systematic errors represented by (μ) were due to the different way of defining the zero values (i.e. the offset). Despite the agreement in ROM, the correlation between the two methods of attachment needs a higher number of subjects to be adequately assessed.

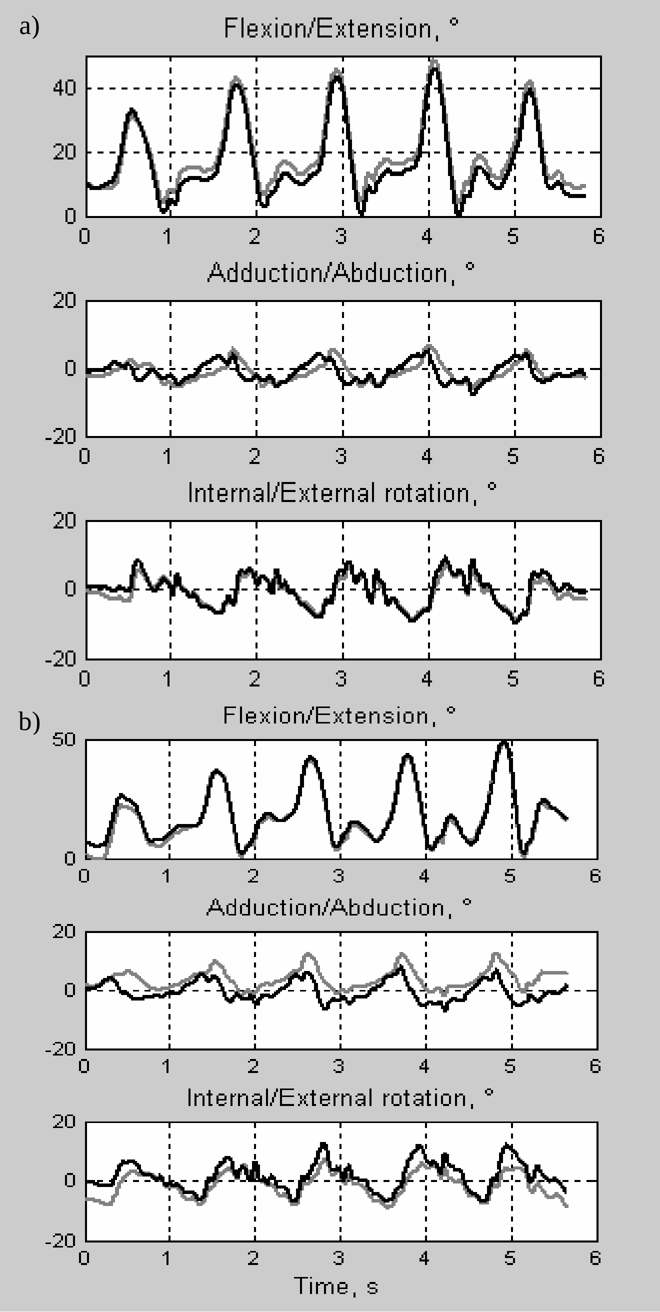

Figure 5. Characteristic 3D knee angles obtained through the inertial and reference system for flat level walks, a) when the inertial system was fixed on the harness and b) on the skin. The black lines correspond to reference system and the gray lines to the the inertial system.

The comparison of these two systems should be extended to more subjects and include different activities. This will permit to characterize the influence of the method of attachment in future. The ambulatory system based on MEMs sensors used in this study in combination with the proposed calibration method provided a very easy-to-use tool to record and calculate the 3D knee joint angles. Moreover the proposed system can be used outside the laboratory, and allows long-time monitoring. Regarding the offset error obtained for some angles, more developments are needed, as currently no functional method is able to precisely define the neutral posture which corresponds to the zero-value. However, the absolute angles values are not always necessary for clinical routine evaluation since usually only the ranges of motion are used. Although in this study, the inertial system was applied to the knee joint, it can be used to investigate the 3D ROM of other complex joints such as ankle, hip or elbow.

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