Journal of Biomechanics 54 (2017) 106–110

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

A novel functional calibration method for real-time elbow joint angles estimation with magnetic-inertial sensors

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ARTICLE INFO

Article history:
Accepted 17 January 2017

Keywords:
Elbow joint angles
Functional calibration
Inertial and magnetic sensors

ABSTRACT

Magnetic-inertial measurement units (MIMUs) are often used to measure the joint angles between two body segments. To obtain anatomically meaningful joint angles, each MIMU must be computationally aligned (i.e., calibrated) with the anatomical rotation axes. In this paper, a novel four-step functional calibration method is presented for the elbow joint, which relies on a two-degrees-of-freedom elbow model. In each step, subjects are asked to perform a simple task involving either one-dimensional motions around some anatomical axes or a static posture. The proposed method was implemented on a fully portable wearable system, which, after calibration, was capable of estimating the elbow joint angles in real time. Fifteen subjects participated in a multi-session experiment that was designed to assess accuracy, repeatability and robustness of the proposed method. When compared against an optical motion capture system (OMCS), the proposed wearable system showed an accuracy of about 4° along each degree of freedom. The proposed calibration method was tested against different MIMU mountings, multiple repetitions and non-strict observance of the calibration protocol and proved to be robust against these factors. Compared to previous works, the proposed method does not require the wearer to maintain specific arm postures while performing the calibration motions, and therefore it is more robust and better suited for real-world applications.

1. Introduction

State-of-the-art technologies for elbow joint angles estimation include optical motion capture systems (OMCSs) and magnetic-inertial measurement units (MIMUs), which contain tri-axial accelerometers, gyroscopes and magnetometers. Regardless of the technology adopted, tracking human body parts is challenging, due to: (i) skin/soft tissue artefacts (Cutti et al., 2005; Schmidt et al., 1999) and (ii) unavoidable misalignments between the observable reference frames and their anatomical counterparts (Fraysse and Thewlis, 2014; Luinge et al., 2007).

In particular, when MIMUs are used for elbow joint angles estimation, only the orientation between the two units can be measured directly. In general, this relative orientation differs from the relative orientation between the anatomical reference frames at the forearm (FA) and the upper arm (UA). Two main approaches have been proposed to overcome this problem (Fraysse and Thewlis, 2014): anatomical and functional methods. Anatomical methods estimate misalignments based on some assumptions about the subject static pose during a short-time interval (Wu et al., 2005; Zhang and Wu, 2011). In (Kapur et al., 2010) the MIMUs of the upper and the forearm were calibrated while the subjects extended the elbow completely, keeping the whole arm orthogonal to the coronal plane. In (Zhang and Wu, 2011), subjects were asked to keep the N-pose (i.e., the neutral pose, with arms neutral besides the body) for few seconds. Functional methods estimate the anatomical rotation axes from the measurements obtained during a set of one-dimensional motions (Cutti et al., 2008; De Vries et al., 2010; Fraysse and Thewlis, 2014; Luinge et al., 2007). The approach suggested in (Luinge et al., 2007) relies on the angular velocity and on the gravity vector measured by MIMUs mounted on the upper arm and on the forearm during simple calibration motions. However, repeatability and robustness of the method were not assessed, and the authors themselves pointed out the need for improving the accuracy of their calibration procedure. In this paper we introduce a novel functional calibration procedure for the elbow joint, which shows good features of accuracy, robustness, and usability for non-expert users.

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http://dx.doi.org/10.1016/j.jbiomech.2017.01.024
0021-9290/

2. Methods

2.1. Experimental setup

A portable measurement system was devised to measure the elbow joint angles, which was composed of two MIMUs (YEI technology, Portsmouth, OH), a 32-bit ARM Cortex-M4 microcontroller, a single-board computer (Handkernel co., GyeongGi, South Korea) and a Li-Po battery (Fig. 1a). The MIMUs were secured to the subjects' arm with Velcro straps. The overall sampling frequency was 220 Hz. A ten-camera OMCS (VICON, Oxford, UK) was used to measure ground-truth body segment orientations. To create auxiliary marker-based local reference frames, reflective marker clusters consisting of three markers were rigidly attached to the housing of each MIMU through wooden sticks. In addition, markers were mounted on the anatomical landmarks suggested in (Wu et al., 2005) (Fig. 1a). Marker data were sampled at 100 Hz. Data from the portable system and from the OMCS were synchronized and upsampled to 250 Hz. Fig. 1a shows a subject wearing the portable system and the IR markers. The IMU and the markers at the shoulder were not considered in this study.

2.2. Proposed calibration method

The elbow was modeled as a kinematic chain with two hinge joints allowing flexion/extension (FE) and pronation/supination (PS) (Cutti et al., 2008; Veeger et al., 1997). The carrying angle (CA) was assumed to be constant, Fig. 1b.

The novel calibration protocol consisted of four steps:

1. UA internal/external rotation while keeping the upper limb fully extended beside the body (pointing down). The angular velocity measured by the UA MIMU was recorded.
2. FA pronation/supination while keeping the upper limb fully extended beside the body. The angular velocity measured by the FA MIMU was recorded.
3. Elbow flexion/extension while keeping the hand parallel to the sagittal plane. The orientation of the FA relative to the UA was recorded.
4. Static N-pose for few seconds. The orientation of the FA relative to the UA was recorded.

Before performing each step, subjects were asked to stay still for one second to reset the gyroscope biases.

Eigenvectors analysis was used to estimate the longitudinal axes of the UA and FA in the corresponding MIMU reference frames (step 1 and 2, respectively) as proposed in (Luinge et al., 2007; De Vries et al., 2010). Unlike previous works, we applied this technique also to estimate the elbow flexion axis (step 3). In addition, the N-pose (step 4) was used to set the zero for the PS (see the Supplementary material for further details).

2.3. Methods for estimating the elbow joint angles

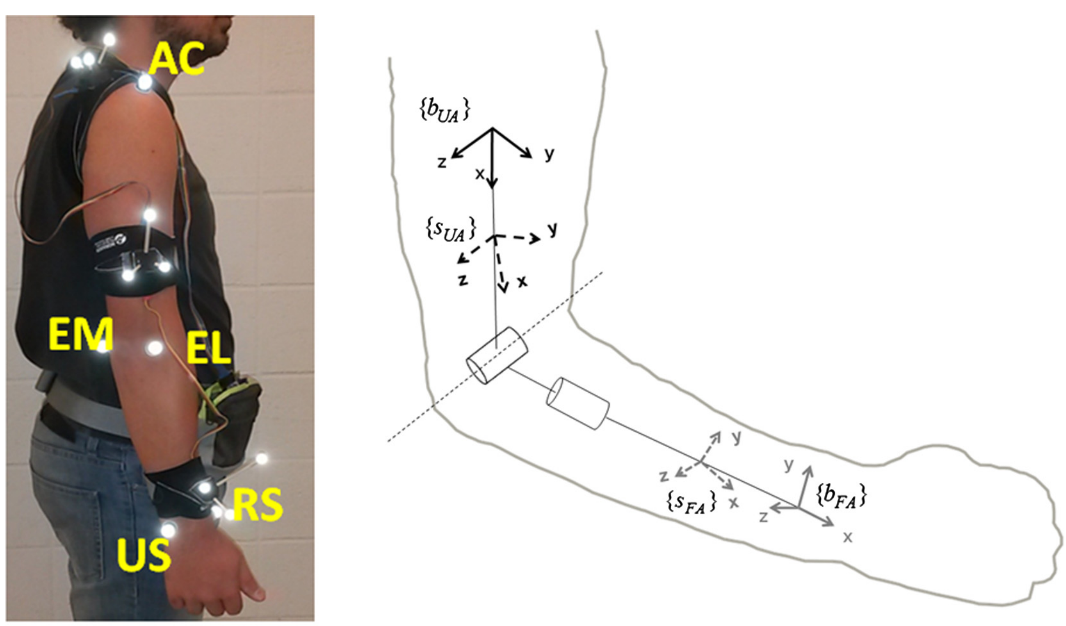
To validate the proposed method, we compared four strategies, which differ in terms of calibration technique (i.e., anatomical or functional, using MIMU or OMCS) and equipment used for joint angle estimation after completion of the calibration step (i.e., MIMU or OMCS). The four strategies were defined as follows:

- **TO-EO**: **T**raditional anatomical calibration with **O**MCS and joint angles **E**stimation with **O**MCS, as suggested in (Wu et al., 2005).
- **FO-EM**: Novel **F**unctional calibration with **O**MCS and joint angles **E**stimation with **M**IMUs. To apply the calibration results relative to the local OMCS reference frames to the MIMUs orientations, the calibration matrices between each MIMUs and the corresponding auxiliary marker clusters were compensated using the procedure introduced in (Chardonnens et al., 2012).
- **FM-EM**: Novel **F**unctional calibration with **M**IMUs and joint angles **E**stimation with **M**IMUs. This is the expected application of the method we propose.
- **FO-EO**: Novel **F**unctional calibration with **O**MCS and joint angles **E**stimation with **O**MCS. This was considered as the ground truth for the joint angle estimation (De Vries et al., 2010; Fraysse and Thewlis, 2014; Luinge et al., 2007).

2.4. Experimental protocol

Fifteen healthy, right-handed subjects (11M, 4F, aged 28 ± 3 years, height 175 ± 8 cm, weight 73 ± 14 kg) participated in the experiment after providing written informed consent. The experimental protocol was approved by the Columbia University Institutional Review Board. Subjects performed three experimental sessions, each consisting of five repetitions of the same trial. In the first part of each trial (calibration), subjects performed the calibration motions required by the novel calibration method. In the second part (validation), six one-dimensional motions separated by 2-s resting periods were executed (three FE motions and three PS motions, whose order was randomized in each trial, Table 1). At the beginning of each session, static anatomical marker positions were acquired with the elbow flexed at approximately 90° and the FA fully pronated. This step was required to apply TO-EO (Wu et al., 2005).

Between the first and the second sessions, MIMUs were taken off and put on again to assess the test-retest reliability of the calibration method. In the third session, the calibration motions were slightly modified to assess the robustness of the method against non-strict observance of the calibration protocol. Subjects were asked to execute the PS motion (step 2) with a different elbow FE angle in each trial, spanning all the FE range of motion (ROM) across the five trials. Similarly, the elbow FE motion (step 3) was executed with five different FA PS angles, ranging from complete pronation to complete supination.



(a) (b)

Fig. 1. (a) A participant wearing the measurement system developed for the present study. The anatomical landmarks selected for the OMCS were the acroniom (AC), the medial and lateral epicondyles (EM and EL, respectively) and the radial and ulnar styloids (RS and US, respectively); (b) Two hinges joint model of the elbow, highlighting the misalignments in place between the MIMUs and the anatomical reference frames. UA reference frames are in black, FA reference frames are in gray. Solid and dashed lines indicate the anatomical and the MIMU reference frames, respectively.