Gait & Posture 59 (2018) 199–205

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Original paper

Camera pose estimation to improve accuracy and reliability of joint angles assessed with attitude and heading reference systems

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ARTICLE INFO

Keywords:
AHRS
IMU
Inertial sensors
3D orientation tracking
Joint orientation
Pose estimation

ABSTRACT

Joint kinematics can be assessed using orientation estimates from Attitude and Heading Reference Systems (AHRS). However, magnetically-perturbed environments affect the accuracy of the estimated orientations. This study investigates, both in controlled and human mobility conditions, a trial calibration technic based on a 2D photograph with a pose estimation algorithm to correct initial difference in AHRS Inertial reference frames and improve joint angle accuracy. In controlled conditions, two AHRS were solidly affixed onto a wooden stick and a series of static and dynamic trials were performed in varying environments. Mean accuracy of relative orientation between the two AHRS was improved from 24.4° to 2.9° using the proposed correction method. In human conditions, AHRS were placed on the shank and the foot of a participant who performed repeated trials of straight walking and walking while turning, varying the level of magnetic perturbation in the starting environment and the walking speed. Mean joint orientation accuracy went from 6.7° to 2.8° using the correction algorithm. The impact of starting environment was also greatly reduced, up to a point where one could consider it as non-significant from a clinical point of view (maximum mean difference went from 8° to 0.6°). The results obtained demonstrate that the proposed method improves significantly the mean accuracy of AHRS joint orientation estimations in magnetically-perturbed environments and can be implemented in post processing of AHRS data collected during biomechanical evaluation of motion.

1. Introduction

Kinematics measurements are important clinical outcomes for mobility assessment. They can be used to assess the impact of age and disease on mobility or to evaluate the effect of a specific intervention [1,2]. Traditional systems used for kinematics assessment (e.g. camera-based systems) have restrictions which limits their suitability for clinical settings (cost, volume, occlusions) [3]. Recent advances in wearables have brought new alternatives for mobility assessment, among which inertial measurement units (IMUs) stand out because of their portability, their size and their relatively low cost [4–10]. IMUs are composed of 3-axis accelerometers and gyroscopes, enabling static 2D orientation and dynamic change in orientation to be estimated. Attitude and Heading Reference Systems (AHRS) are an extension of traditional IMUs which includes magnetometers to enable full 3D orientation estimation in a global reference frame based on gravity and magnetic North (i.e. Inertial reference frame). Joint kinematics can therefore be derived from two AHRS positioned on adjacent segments. It is, however, well documented that orientation estimation based on AHRS is affected by magnetic perturbations [11–14]. To overcome this limitation, most estimation algorithms include a magnetic compensation process that is proven to work well for transient perturbations [13,15]. But, under sustained magnetically perturbed conditions, AHRS tends to adjust the definition of its Inertial frame to adapt to its current environment. Consequently, a difference in the definition of the Inertial frames may arise between AHRS, invalidating the assumption of equivalence of reference frames required for joint orientation estimation. This effect has been observed during regular gait assessment, specifically at the ankle level [12]. Indeed, common building construction material can perturb the magnetic field at floor

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http://dx.doi.org/10.1016/j.gaitpost.2017.10.016
Received 13 March 2017; Received in revised form 7 September 2017; Accepted 12 October 2017
0966-6362/

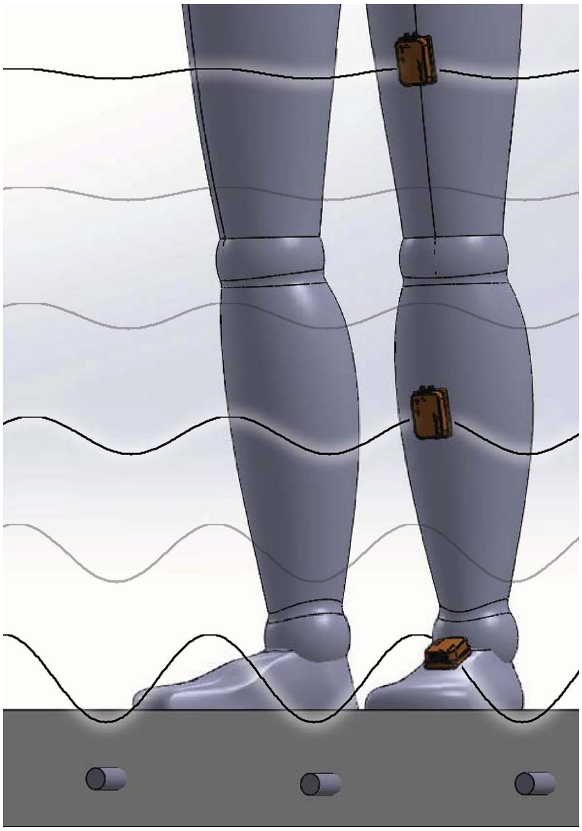

Fig. 1. Magnetic Field Problem for Joint Orientation Assessment using AHRS. Common floor material in building is sufficiently ferrous to perturb the magnetic field. That perturbation decreases as the distance from the floor increases.

level, which perturbations decrease in importance as we move away from the floor [12,16]. Thus, the magnetic field sensed at the foot level is different from the one measured at the shank (Fig. 1). Assessing the ankle's angular motion during gait analysis using AHRS can therefore be problematic [12,17].

To overcome these problems, different avenues ranging from the replacement of the magnetometers by potentiometer [18] to the periodic use of a predetermined position and orientation [14] were investigated in the literature. Although interesting, these approaches are condition-specific. More recently, Lebel et al. have shown that relative accuracy can be improved when initial differences in Inertial reference frames are compensated [19]. A similar investigation was performed by Palermo et al. [12] who used the magnetic field distortion at trial initiation, estimated from an optoelectronic system, to correct AHRS' heading errors during gait assessment. This approach of initial reference frame compensation to calibrate the sensors is promising, but the current technics for the estimation of the appropriate correction limit its usability.

Pose estimation is a technic used in different fields of study such as augmented reality and autonomous navigation to provide changes in position and orientation of a 3D object based on a 2D photographs [20,21]. The current study investigates a trial calibration technic based on pose estimation to compensate the differences in reference frames induced by magnetic perturbations at trial initiation when using AHRS in a clinical biomechanics context. Specifically, the objectives of this study are: (1) to assess the accuracy and the reliability of the pose estimation principle for relative orientation estimation; and (2) to evaluate the impact of using the camera pose estimation correction (CPEC) on AHRS relative orientation estimation accuracy, both in controlled and human conditions.

2. Materials and methods

This study investigates a trial calibration technic based on pose estimation to improve accuracy of relative orientation assessed with AHRS, in comparison with a camera-based motion-capture system.

2.1. AHRS for segment orientation assessment

Orientation is assessed using two MTx modules (Xsens Technologies) connected to a Xbus kit transmitting the data wirelessly to a receiver, connected to a PC. Data acquisition was performed at 100 Hz using MT Manager Version 4.1 configured for human motion.

2.2. Pose estimation

The proposed pose estimation algorithm is derived from the work of Vogiatzis and Hernández which uses multi-view stereo principle to extract 3D information from a 2D photograph [22–25]. The authors use a planar circular dot pattern placed underneath an object to determine the change in orientation of that object using a regular photograph. Briefly, circular dots projected on a 2D surface with a certain angle are represented as ellipses, which size varies with the distance of the object to the camera. Through a best-fit ellipse principle applied on a known multi-dot pattern, Vogiatzis and Hernández's algorithm can determine the change in orientation of an object [23]. The algorithm was adapted to enable its use with two similar dot patterns within a single photograph. The modified algorithm outputs the orientation of both patterns in the same camera frame, allowing to compute the relative orientation between the objects. Reliability, stability and accuracy of the adapted algorithm were verified prior to this study using two rigid bodies, each composed of a dot pattern and a set of active markers, placed on a table. Reliability was assessed taking 10 pictures of the patterns with the camera fixed on a tripod, 1.2 m away. Stability was assessed from multiple pictures ($n = 5$) taken at 1.2 m, 2.1 m and 3.4 m, without a tripod. Finally, tracking accuracy was verified at the same three distances, varying the angle between the two rigid bodies from -90° to $+90^\circ$. Analyses revealed a reliability of $1.5^\circ \pm 0.1^\circ$, a stability varying between 1.1° and 1.3° depending on the distance, and a tracking accuracy of 0.9°. A minimal angle of view of 10° is recommended to ensure reliability of the algorithm. Details on the validation steps are available as Supplementary material to the present manuscript.

2.3. Orientation correction

Relative orientation between two AHRS can be computed based on the assumption that the two AHRS refer to the exact same Inertial frame.

Let $\underline{q}_{AHRS1}I_1$ be the orientation of AHRS1 in its Inertial frame; and
$\underline{q}_{AHRS2}I_2$ be the orientation of AHRS2 in its Inertial frame
If $I_1 = I_2 = I$ then

$$\underline{q}^{AHRS1}_{AHRS2} = \underline{q}_{AHRS1}I^{-1}{**}\,\underline{q}_{AHRS2}I, \qquad (1)$$

where ** denotes a quaternions multiplication.

However, persistent magnetic perturbations may affect that relationship of equivalence in Inertial frames, invalidating equation Eq. (1). In these cases, the change in orientation of a single AHRS relative to its initial trial orientation is still reliable, but additional information is required to link both modules' orientations to assess relative sensor kinematics. A single photograph coupled with a pose estimation algorithm (CPEC) can complement the equation, providing the required initial relative orientation link ($\underline{q}^{AHRS1ini}_{AHRS2ini}$) (Eq. (2)).