Assessing the Validity of Attitude and Heading Reference Systems for Biomechanical Evaluation of Motions
A Methodological Proposal

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Abstract: *Background*: Attitude and Heading Reference Systems' (AHRS) popularity in biomechanics has been growing rapidly over the past few years. However, the limits of operation and performances of such systems for motion capture are highly dependent upon their conditions of use and the environment they operate in. The objectives of this paper are to: (1) propose a methodology for the characterization of the criterion of validity of accuracy of AHRS in a human biomechanical context; and (2) suggest a set of outcome measures to assess the accuracy of AHRS. *Methods*: The criterion validity of accuracy is established using an optical motion tracking gold standard under standardized human motions. *Results:* Global assessment of accuracy is derived by comparing the orientation data provided by the AHRS to those given by the gold standard using a coefficient of multiple correlation. Peak values and RMS difference between both sets of orientation data are also analysed to complete the accuracy portrait. The methodology proposed herein is verified for the knee during regular walk. *Conclusion*: The proposed methodology and analyses take into consideration the complexities and processes required to assess the accuracy of AHRS in their context of use and provide a standardized approach to report.

1 INTRODUCTION

Functional mobility is a fundamental aspect of quality of life. The evaluation of mobility impairments is therefore crucial to many clinical decisions in fields ranging from rehabilitation to geriatrics. Traditional approaches for biomechanical evaluation of motion include optical motion capture systems and magnetic trackers. Although well known for their capacity to provide a highly accurate tracking within a given capture volume, accurate tracking for optical motion capture systems is limited to portions of the capture volume with a clear line of sight between the cameras and the markers. The size of the capture volume is often further constrained by the number and the resolution of the cameras used. Furthermore, optical motion capture systems can't be used easily outside of a laboratory environment. Magnetic trackers offer excellent accuracy but are sensitive to magnetic perturbations in the capture volume and their accuracy is limited to short operating ranges between transmitter and receivers due to the decay of the magnetic field. Traditional motion capture

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approaches all have limitations and trade-offs in terms of accuracy, validity/reliability, time/cost, training/expertise and real-world generalizability.

3D inertial motion tracking devices, also referred to as Attitude and Heading Reference Systems (AHRS), have been gathering interests by researchers and end-users as an alternative to traditional optical and magnetic motion capture and analysis systems for biomechanical evaluation of motion. AHRS are composed of inertial sensors (accelerometers, gyroscopes and magnetometers) which outputs are fed into a fusion algorithm in order to determine the orientation of a rigid body in a global reference frame, defined by gravity and magnetic North. An AHRS attached on a limb will therefore enable assessment of changes in orientation for that limb over time. Analysis of orientation variations can be used, for example, to study trunk kinematics of older adults during transfer activities and assess muscle and postural control impairments (Giansanti et al., 2007; Horak et al., 2013). The AHRS ability to express their orientation in a global reference frame also allows them to be used in pairs, to reconstruct joint kinematics. In the past few years, such approach has also been used, for example, to study gait parameters (Ferrari et al., 2010a; Horak et al., 2013) as well as upper limb kinematics (Cutti et al., 2008, Luinge et al., 2007). The long-term recording capabilities of AHRS makes them suitable to appraise changes and variability of mobility features during specific scenarios such as sustained walking or stair climbing over one floor.

The use of AHRS for biomechanical evaluation of motion also has limitations. The required measurement accuracy, depending on the scenario and biomechanical features studied is a determining factor in choosing to use AHRS. Several studies have explored the validity of AHRS orientation measurement on market-available systems (Brodie et al., 2008; Cutti et al., 2006; De Agostino et al., 2010; Picerno et al., 2011; Lebel et al., 2013). Some studies focussed on assessment of accuracy using a Plexiglas plank on which multiple units of the same AHRS model were aligned. Using such setup, Picerno et al. (2011) concluded that under multiple static conditions, the tested modules define their orientation differently, with a worst-case discrepancy of 5.7°. Using a similar setup under dynamic conditions, Cutti and al. (2006) revealed an effect of velocity and direction of motion on the precision of the orientation measurement. The concepts evoked in these studies for a single system were confirmed in a recent study from Lebel et al. (2013) which used an instrumented Gimbal table in order to assess, under controlled conditions of motions, the criterion of accuracy of the orientation measurement of different types of commercially available AHRS. This study has shown a significant effect of velocity for all three systems tested, although the extent of the effect varied among the different systems. The discrepancies between the numerical results observed throughout those studies suggests an effect of the environment on the accuracy of the results. Indeed, the orientation data provided by AHRS is *estimated* from inertial sensors data using a fusion algorithm. Although the type of fusion algorithm varies between AHRS models and companies, they all face the same challenge: the filter must autonomously differentiate between true motion, change in environment and environmental perturbations. Hence, the tuning of the filter as well as the magnetic compensation used significantly affect the computation of the estimated orientation at a given time, and variations in either conditions (environment or type of motion) is subject to impact the precision of the orientation data provided.

The variation in accuracy due to the type of motion, the velocity and the environment reported in all those study motivates the definition of a methodological approach for validating the accuracy of AHRS in its actual biomechanical context of use. To do so, a step-wise approach is suggested in order to separate the validation of the technology itself from the validation of the biomechanical model used to interpret those measurements. The present paper focuses on the technology validation portion and therefore does not consider the use of any biomechanical model in the validation process.

The scope of the present paper is (1) to propose a protocol for the characterization of the criterion of validity of AHRS in a biomechanical context; (2) to suggest a set of outcome measures for biomechanical features precision assessment; and (3) to present typical validation results obtained using this protocol.

2 MATERIALS AND METHOD

2.1 General Setup and Assumptions

The proposed methodology aims at validating the data provided by AHRS in a biomechanical context. Measurement validation refers to the description of the quality of the measurement which can be characterized according to different concepts, namely the accuracy, the precision and the trueness of the measurement (Menditto et al., 2006). According to the ISO nomenclature, accuracy of measurement refers to the “closeness of agreement between a quantity value obtained by measurement and the true value of the measurand” (CAN/CGSB-158.1-98, 1998) while the precision can be defined as “the closeness of agreement between independent test results obtained under stipulated conditions” (ISO 3534-1,1993). Finally, the trueness refers to “the closeness of agreement between the average value obtained from a large series of test results and an accepted reference value” (ISO 3534-1, 1993). The validation of AHRS measurements is therefore accomplished by evaluating the accuracy of AHRS data compared to an optical motion capture gold standard while a subject executes a set of pre-determined tasks. Furthermore, accuracy evaluation between the gold standard and the AHRS relies upon the underlying assumptions that both systems are exposed to the exact same movement at the same time and that the gold standard is accurate.

2.2 Optical Markers Rigid Body and AHRS

The assumption that both systems undergo the same motion at the same time is addressed with the use of non-ferrous rigid bodies incorporating markers and AHRS units tested (Figure 1). The number of markers to be included in each rigid body depends upon the cameras visibility during motion and the nature of the markers (passive or active). In the case of passive markers, a minimum set of four markers is suggested to allow redundancy and to provide more flexibility in the configuration of the rigid bodies. Chosen configurations shall ensure easy differentiation between the different rigid bodies used simultaneously for enhanced tracking capabilities. Each AHRS is then solidly affixed to a rigid body (Figure 1, panel B) and the created bundle is ready to be placed on the body segment targeted for evaluation.

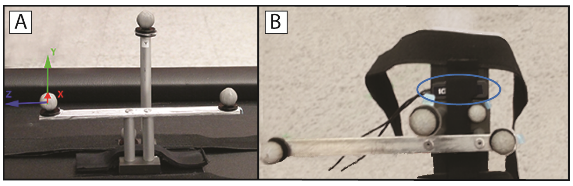

Figure 1: Rigid Body (A) General View (B) with AHRS.

2.3 Gold Standard Accuracy Assessment

Optical motion capture systems are often considered the reference for accurate kinematic assessment of motion in biomechanics. Very few studies however report on the accuracy of these systems for specific contexts of use. Indeed, their accuracy vary according to the cameras lens distortion, the resolution, the position and the number of cameras available for the defined volume of acquisition, the calibration procedure and the markers properties (Windolf et al., 2008). In order to ensure an acceptable level of truthfulness to compare the accuracy of AHRS to a given gold standard in the defined set-up, the following quality check procedure is proposed.

The first step of the process is performed at the markers’ position level and is based on the assumption that the relative distances between markers on a specific rigid body is constant. Referring to the definitions listed in section 2.1, the precision of the system in locating the position of a marker can be estimated by computing the variation in the relative distances between rigid bodies’ markers. To do so, relative distances between all markers comprised within the same rigid body shall be computed for all valid orientation data recorded during a representative trial (i.e. if an orientation data is provided for a rigid body at a specific timestamp, it is then relevant to compute the distances between its markers). The mean relative distance, computed for each segment, defines the reference value for that segment. It is indeed reasonable to do so since the rigid body markers are close enough to assume that a bias affecting the measured position of a specific marker will affect its companions in a similar manner, hence cancelling the effect of the bias on the relative distance measurement. Although the computation of the standard deviation on the markers’ relative distance measurements provides an idea of the overall accuracy of the system in its specific context of use, the impact of such variations on the orientation data needs to be further addressed.

The second part of the procedure therefore focuses on the evaluation of the accuracy of the optical system at the orientation level through a worst-case Monte Carlo analysis where only the closest three markers of a rigid body will be used by the system to reconstruct the rigid body’s attitude. This step requires the identification of those three markers and the definition of a sphere of uncertainty around each of those markers, which radius is equivalent to the mean standard deviation computed on relative markers distances for that rigid body. Orientation of the rigid body can be assessed from the vectors defined by those three points. A Monte Carlo analysis then enables the assessment of the precision of the optical gold standard for the specific context of use by computing the standard deviation on the rigid body's orientation estimate. The difference between the mean rigid body's attitude (computed from Monte Carlo results) and the reference orientation value (computed from the reference segment distances defined) constitute the level of trueness of the system. A global appreciation of the accuracy of the optical system in its conditions of use can finally be derived by combining the computed trueness and precision of the system in a 95% confidence interval.

2.4 Comparison of Orientation Measurement from Different Systems

A rigid body's orientation is commonly represented using a set of three elemental and independent rotations allowing the definition of the current spatial orientation of the rigid body based on a known initial reference frame. Euler angles are a good example of such approach. Although intuitive, these representations are subject to gimbal lock, a problem caused by the alignment of two of the rotational axes during the independently-segmented rotational process, affecting the overall ability to describe the rigid body's orientation.

An alternate representation to elemental rotations for the definition of a rigid body's attitude is the quaternion. A quaternion is an angle-axis orientation representation which defines the change in orientation of a rigid body in a single step, using a four-component vector. Although far less instinctive than elemental rotations, the intrinsic redundancy contained within the quaternion's definition ensures avoidance of singularities otherwise referred to as gimbal lock. The current protocol proposes to use the global range of motion (ROM) computed directly from the quaternion's first vector component, as a comparison baseline between the inertial and the optical motion tracking systems instead of trying to decompose the motion using a 3D descriptive approach. From the definition of quaternion:

$$\underline{q} = \begin{bmatrix} q0 \\ q1 \\ q2 \\ q3 \end{bmatrix} = \begin{bmatrix} \cos(\varphi/2) \\ a_x \sin(\varphi/2) \\ a_y \sin(\varphi/2) \\ a_z \sin(\varphi/2) \end{bmatrix} = \begin{bmatrix} \eta \\ \underline{\varepsilon} \end{bmatrix} \qquad (i)$$

$$, where \quad \eta = \cos(\varphi/2) \quad and \quad \underline{\varepsilon} = \underline{a}\sin(\varphi/2)$$

$$\therefore ROM, \varphi = 2a\cos(q0) \qquad (ii)$$

The assessment of accuracy using any 3D descriptive approach would require an alignment protocol between the two systems' reference frame, which accuracy can be debated. Theoretically, the inertial reference frame can be defined by measuring the local magnetic North and the gravity. The optical reference frame being known to the user, one can then deduce the alignment relationship between the inertial and the optical reference frame. However, such alignment procedure presents certain flaws which may affect its accuracy. First of all, it assumes intrinsic knowledge of the AHRS algorithm regarding the global reference definition: Is the algorithm compensating for the angle between the gravity and the Earth's magnetic North according to the location? Does the definition considers the theoretical value for the Earth's magnetic field or does it consider the initial measured value? Perhaps a mixture of both approaches? Furthermore, typical biomechanical lab, just like regular environments, present certain magnetic variations (De Vries et al., 2009; Bachmann et al., 2004). In order to adapt to such changes in environment, AHRS are known to allow slight deviations of their inertial frame definition under constrained conditions. Hence, one cannot assume the measured relationship between the inertial reference frame and the optical reference frame, would it be accurate, to be constant in time as the module is moved in the environment. Expressing accuracy using the global ROM as a baseline for comparison over any other descriptive 3D quantities is therefore proposed in an effort to concentrate the evaluation on the ability of the module to detect movement while minimizing any other sources of errors.

2.5 Absolute and Relative Accuracy of Orientation Measurements from AHRS

In biomechanics, inertial sensors are sometime used solely, to measure the variation in the orientation of a segment, or in pairs, to measure the angle at a specific joint. In order to fully address the question of accuracy for AHRS in biomechanics, we therefore propose to divide the accuracy notion into absolute and relative accuracy, which concepts are further detailed in the following sub-sections. The term accuracy is herein used as both concepts refers to a general appreciation of the quality of the measurement.

2.5.1 Absolute Accuracy

In the current context, the concept of absolute accuracy is directly linked to the ability of a system to measure a variation in the orientation of a segment over time. Assessment of absolute accuracy criterion is therefore verified by comparing the global change in orientation measured by an AHRS to the global change in orientation measured by the optical motion tracking system for a specific segment.

2.5.2 Relative Accuracy

Relative accuracy assessment refers to the capability of a pair of module to measure joint angle changes (i.e. joint angle accuracy). In addition to the ability of the involved modules to track accurate motion of the segments around the specific joint, the relative accuracy concept includes the ability of both modules to express the independently-measured motion in a matching reference frame so to accurately define joint motion. The concept of relative accuracy therefore relies upon a combination of the inter-sensors consistency and the trueness of the reference system of each sensor. The direct repercussion of this type of accuracy on biomechanical measurement motivates the introduction of the relative accuracy concept.

3 OUTCOMES AND DATA REDUCTION FOR ORIENTATION ACCURACY EVALUATION

The concept of accuracy of angular measurement within a context of a biomechanical evaluation of motion varies according to the evaluation's purpose. The following sub-sections describe how both concept of accuracies are considered in the proposed protocol in an effort to provide a validation process as complete as possible.

3.1 Global Assessment of Validity and Fidelity

Global assessment of validity refers to the capacity of the system to measure the motion performed. This criterion is verified using the coefficient of multiple correlation (CMC) adapted for the evaluation of the similarity of biomechanical data acquired synchronously through different Medias (systems or protocols) by Ferrari et al. (2010b).

$$\mathrm{CMC} = \sqrt{1 - \frac{\sum_{g=1}^{G}\left[\frac{\sum_{p=1}^{P}\sum_{f=1}^{F}\left(Y_{gpf}-\overline{Y}_{gf}\right)^2}{GF_g(P-1)}\right]}{\sum_{g=1}^{G}\left[\frac{\sum_{p=1}^{P}\sum_{f=1}^{F}\left(Y_{gpf}-\overline{Y}_{g}\right)^2}{G(PF_g-1)}\right]}} \qquad (iii)$$

,where P corresponds to the number of waveforms to evaluate through G cycles, F_g relates to the number of frames measured by gait cycle, $\bar{Y}_{gf}$ is the average ordinate of frame f of the g^{th} cycle over the P waveforms, and $\bar{Y}_g$ is the overall mean ordinate for the g^{th} cycle over the P waveforms.

This specific version of the CMC is a measure of the overall similarity of two waveforms which takes into consideration the effect of offset, correlation and gain in its similarity assessment, while ignoring inter-cycle variability.

The definition of the CMC can be used as an accuracy index in both absolute and relative accuracy concepts, through the analysis of the orientation waveform issued by a single AHRS module with its matching waveform from the optical system (e.g. trunk variations during sit-to-stand) or looking at the variation in the joint angle waveform computed from the related AHRS modules to the joint angle waveform computed from the optical system measurements (e.g. knee angle during sustained walking).

The global assessment of fidelity is evaluated using the RMS error between the two waveforms in order to give an appreciation of the precision of the measurement within a given trial. The combination of the CMC and the RMS error reported for a specific context of evaluation therefore gives a global appreciation of the quality of the measurement for that context.

3.2 Peak Accuracy

Orientation data is *estimated* by AHRS from inertial sensors data using a fusion algorithm (e.g. Kalman filter). Although powerful, the effectiveness of fusion algorithms is known to be directly related to the quality of the algorithm parameters' adjustment. Indeed, optimal tuning not only considers the quality of the sensors over the filter prediction capacity, but also the desired filter's reactivity to a change in motion versus its robustness to a perturbation in the environment. According to the quality of the filter's tuning, the accuracy of the orientation data provided by an ARHS is therefore expected to fluctuate during a given motion, with situations such as motion initiation and changes in direction being identified among the most challenging circumstances.

Maximal range of motion is one of the feature of interest in biomechanical evaluations of motion which involves measurements at those particularly challenging situations. Analysis of accuracy at these specific moments is therefore essential. To define this error, we propose to compute the mean absolute difference as well as the RMS error between the orientation provided by the AHRS and the orientation measurement provided by the optical motion tracking system for these change in direction. Combination of those values gives an appreciation of the accuracy at these specific peak situations.

4 IN VIVO APPLICATION

The proposed methodology was applied in the validation of a specific AHRS under human conditions of motions with 21 adults. For this specific application, the protocol was based on a clinical test recognized as reliable for mobility capabilities assessment, the Timed Up and Go (TUG). This test includes a sit-to-stand transfer, a walking portion, a 180° turn and ends with a stand-to-sit transfer. For illustration purpose of the concepts and methods presented before, results from one subject only are reported.

The AHRS used to illustrate the evaluation procedures is the IGS-180 motion capture suit (Animazoo, 2013). The system includes 17 AHRS, allowing full body kinematics reconstruction. A joint targeted for evaluation in the study which intends to use the IGS-180 is the knee. The validation protocol therefore focussed on the AHRS placed on the thigh and the shank.

The current protocol used the Vicon optical motion capture system with 12 cameras as a gold standard (Vicon, 2013). Each targeted AHRS was coupled with a rigid body as explained in Section 2.2. Since the selected optical motion capture system uses passive markers, specific care was given to the design of the rigid bodies so to ensure optimal tracking. AHRS were solidly affixed to their matching rigid body and then, to the subject, as shown in Figure 2.

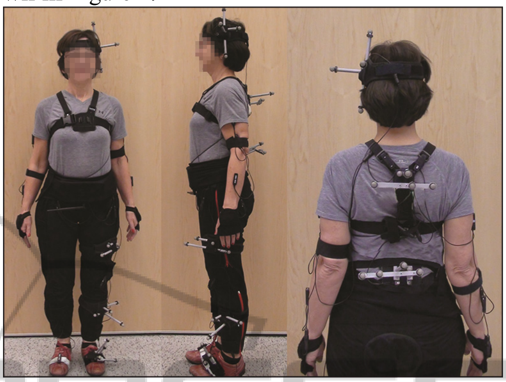

Figure 2: IGS-180 with Vicon Rigid Bodies.

5 VALIDATION RESULTS

Preliminary results for knee angle validation are presented herein to illustrate the feasibility of the proposed methodology to assess accuracy of AHRS in a biomechanical context. The analysis of the accuracy of the optical gold standard was performed for the rigid bodies located on the thigh and the shank. As explained in section 2.3, the variation in the relative distances between the four markers comprised within each of the rigid body was first computed during a typical trial. In this case, the rigid body on the thigh and the shank has shown a standard deviation in the markers' relative distances of 1.04mm and 1.02mm respectively. A sphere of uncertainty with a radius equivalent to the computed standard deviation (1.04mm for the thigh and 1.02mm for the shank) was then defined around the three closest points of each rigid body. A Monte Carlo analysis revealed a trueness close to 0º (thigh: 0.0014º; shank:-0.0002º) and precision of 0.35º (thigh: 0.3339º; shank: 0.355º), giving a 95% confidence interval of [-0.7, 0.7].

Figure 3 illustrates the knee angle measured synchronously by the two systems, the Vicon and the IGS180, during a slow walk. The different cycles measured by both system are visually very alike, which similarity is reflected in the computed CMC value of 0.995. Analysis of the difference between the curves shows that the accuracy varies along the motion with the maximum errors being reached at the change in direction.

Table 1 reports the chosen indexes for global and peak accuracy assessment, all for the knee angle during sustained walking (12 to 18 cycles of walk), but varying either the speed or the path (i.e. the environment) of the walk. Increasing the pace of the walk slightly decreased the CMC (0.991) and increased both the RMS difference and the mean difference at maximum ROM (respectively, 3.1° and 2.6°). Similarly, slow walking along a magnetically perturbed path also affects the validation indexes.

Table 1: Accuracy Assessment in Different Conditions.

	SLOW WALK	FAST WALK	SLOW WALK PERTURBED
CMC	0.995	0.991	0.911
RMS difference	2.4°	3.1°	8.8°
$\lvert\overline{\Delta\varphi_{peak}}\rvert$	2.0°	2.6°	12.3°
RMSE$_{peak}$	2.5°	3.3°	12.5°
Nb cycles	18	12	18

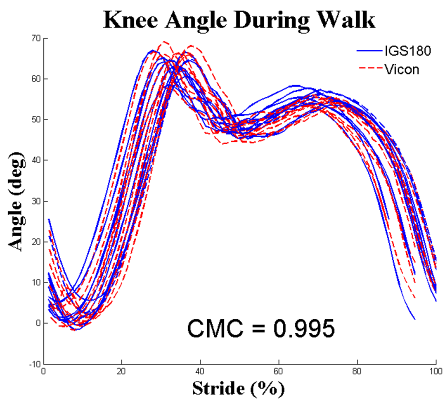

Figure 3: Knee Angle during Walk.

6 DISCUSSION

Optical motion capture systems are often considered the reference for accurate kinematic assessment of motion in biomechanics. Although their accuracy is known to vary according to a number of factors, very few studies report on the accuracy of these systems for specific contexts of use. The methodology proposed herein is intended to be implemented in the system actual context of use, hence considering both the material constraints (cameras, settings, calibration, markers properties, etc.) as well as the type of motion performed.

Reported accuracy of AHRS also vary according to their conditions of use, including the environment and the type of motion performed. The proposed protocol is specifically designed to verify the accuracy of AHRS in their context of use and the chosen indexes were shown appropriate to assess the impact of velocity, environment and time on the accuracy of the features of interest. Preliminary validation of the protocol confirms the feasibility and added value of this evaluation strategy.

7 CONCLUSIONS

The proposed protocol and analyses take into consideration the complexities and processes required to assess the accuracy of AHRS in their context of use and provide a standardized approach to report.

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