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Sensor-to-body calibration procedure for clinical motion analysis of lower limb using magnetic and inertial measurement units

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ABSTRACT

Magnetic and Inertial measurement units (MIMUs) have become exceedingly popular for ambulatory human motion analysis during the past two decades. However, measuring anatomically meaningful segment and joint kinematics requires virtual alignment of the MIMU frame with the anatomical frame of its corresponding segment. Therefore, this paper presents a simple calibration procedure, based on MIMU readouts, to align the inertial frame of the MIMU with the anatomical frames, as recommended by ISB. The proposed calibration includes five seconds of quiet standing in a neutral posture followed by ten consecutive hip flexions/extensions. This procedure will independently calibrate MIMUs attached to the pelvis, thigh, shank, and foot. The accuracy and repeatability of the calibration procedure and the 3D joint angle estimation were validated against the gold standard motion capture system by an experimental study with ten able-bodied participants. The procedure showed high test-retest repeatability in aligning the MIMU frame with its corresponding anatomical frame, i.e., the helical angle between the MIMU and anatomical frames did not significantly differ between the test and retest sessions (except for thigh MIMU). Compared to previously introduced procedures, this procedure attained the highest inter-participant repeatability (inter-participant coefficient of variations of the helical angle: 20.5–42.2%). Further, the proposed calibration would reduce the offset errors of the 3D joint angle estimation (up to 12.8 degrees on average) compared to joint angle estimation without calibration (up to 26.3 degrees on average). The proposed calibration enables MIMU to measure clinically meaningful gait kinematics.

1. Introduction

In the past two decades, magnetic and inertial measurement units (MIMUs) have been widely used in biomedical applications such as gait analysis, fall detection, and physical activity analysis (Iosa et al., 2016; Nazarahari and Rouhani, 2018). Compared to current gold standard motion capture technologies, which require a dedicated laboratory, MIMUs can be used in the free-living environment for ambulatory human motion monitoring and are more affordable. However MIMUs measure acceleration and angular velocity in their own inertial frame, which is a limitation for biomedical applications that require the information in anatomical frames (AFs) of the body (Favre et al., 2009). This issue can be resolved by finding a transformation that maps, through a calibration procedure, the MIMU frame to the targeted AF.

The methodologies presented in the literature to determine the sensor-to-body transformation (will be referred to as calibration hereafter) mainly used a combination of functional tasks or postures (Filippeschi et al., 2017; Picerno, 2017). For example, Favre and colleagues used MIMU to measure the angular velocity during passive shank flexion/extension and abduction/adduction and determined shank AF (Favre et al., 2009). For the thigh, AF was defined such that the anatomical knee joint angles equaled zero during standing posture. This approach, however, propagated the errors in shank calibration into thigh calibration and provided no calibration procedure for pelvis and foot. Cutti and colleagues proposed "Outwalk," including a protocol for MIMU attachment and calibration, for joint kinematic measurement in a newly defined anatomical system (Cutti et al., 2010). However, this protocol required a complicated procedure and close supervision of an experienced operator.

Palermo and colleagues proposed a two-step calibration including acceleration measurement during two pre-defined static postures (Palermo et al., 2014). Although this method provided a powerful tool for lower limb calibration, it required precise configuration of the segments during the two static postures. Further,

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misalignment between segment orientation during the two static postures in the sagittal plane could affect the calibration accuracy. Picerno and colleagues introduced instrumented calibration of MIMUs for knee kinematic measurement using an ad hoc tool (Picerno et al., 2008). While this method can be helpful for clinical purposes, it can be time-consuming compared to the previously mentioned functional approaches. Ligorio and colleagues introduced a four-step calibration procedure for the clinical elbow joint angle estimation using functional movements and eigenvector analysis. Although this procedure was successfully validated for upper-extremities, the functional movements might not be optimized for lower extremities (Ligorio et al., 2017).

The primary objective of this work was to facilitate clinical motion analysis using MIMUs by developing and validating an accurate and repeatable calibration procedure for MIMUs attached to the pelvis, thigh, shank, and foot. To this end, we first introduced a novel procedure to evaluate the quality of the calibration directly. Second, the repeatability of the proposed calibration was evaluated using commercially available MIMUs. Then the accuracy and repeatability of the proposed calibration were compared with similar approaches in the literature. Finally, the effect of the proposed calibration on joint angle measurement was evaluated during over-ground walking.

2. Materials and methods

2.1. Measurement systems

Four MIMUs (MTws, Xsens Technologies, NL) were used to analyze the kinematics of the pelvis, thigh, shank, and foot, as shown in Fig. 1(a) and (b). The MIMUs recorded motion data synchronously with a sampling frequency of 100 Hz. Each MIMU was fixed on a rigid plate equipped with retro-reflective markers, and the plates were attached over body segments via medical tape. As a gold standard reference system, a motion capture system (VICON, Oxford Metrics Group, UK) with eight cameras recorded motion data synchronously with MIMUs. Cameras recorded the position of the markers on the plates and anatomical landmarks of the pelvis, thigh, shank, and foot, as outlined by Cappozzo et al. (1995).

2.2. Sensor-to-body alignment procedure

The AFs were defined based on Cappozzo et al. (1995) but their axes were modified as recommended by the ISB (Wu and Cavanagh, 1995). The joint coordinate system (Grood and Suntay, 1983) was used to obtain three clinical rotations of each joint: flexion/extension (FE), abduction/adduction (AA), and internal/external rotation (IE) for hip and knee; and dorsi/plantar flexion (DP), inversion/eversion (IV), and internal/external rotation (IE) for ankle.

The sensor-to-body transformation, obtained via functional calibration, determines the orientation of the segment's AF (${}_{AF}{}^{G}R$) as a function of the orientation of the MIMU frame attached to that segment (${}_{SF}{}^{G}R$):

$$ {}_{AF}{}^{G}R = {}_{SF}{}^{G}R \cdot \left({}_{SF}{}^{AF}R_{MIMU}\right)^{T}, \tag{1} $$

where ${}_{SF}{}^{AF}R_{MIMU}$ is the calibration rotation matrix, constant throughout the trial.

To obtain ${}_{SF}{}^{AF}R_{MIMU}$, the proposed calibration procedure consists of five seconds of quiet standing followed by ten active hip FE (or AA), as seen in Fig. 1(c) and (d). For hip FE (or AA), participants were asked to lock their knee and ankle joints and control their movement such that their leg moved in one plane (participants were free to select their desired range of motion and FE/AA speed).

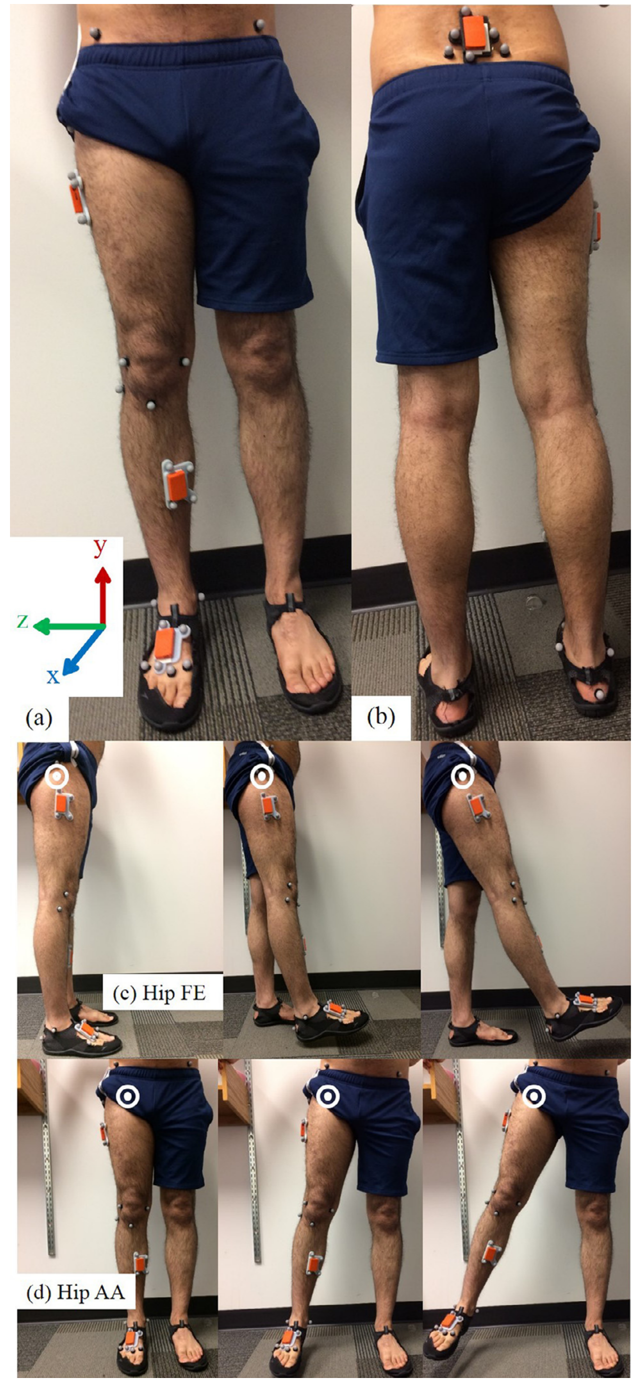

Fig. 1. The measurement system including MIMUs, plates, and retro-reflective markers on anatomical landmarks of (a) thigh, shank, foot, and (b) pelvis, and Calibration procedure including quiet standing followed by consecutive active hip (c) flexion/extension (FE) and (d) abduction/adduction (AA). The MIMUs' coordinate systems were defined such that the x-axis pointed into anterior direction, y-axis pointed into upward direction, and z-axis pointed lateral direction toward the right, Fig. 1(a).

Acceleration readouts during quiet standing, and planar angular velocity during functional movements were used to calculate ${}_{SF}{}^{AF}R_{MIMU}$ as described in the Supplementary Material A.

2.3. Experimental protocol

To validate the proposed procedure, an experimental study was conducted with ten able-bodied participants (all male, 24 ± 3 years old). The Research Ethics Board Committee of the University of Alberta approved the study protocol, and written consent was obtained from all participants. Each participant performed six different movements: hip FE (20 times) as in Fig. 1(c); hip AA (20 times) as in Fig. 1(d); passive knee FE (by study coordinator); passive knee AA (by study coordinator); quiet standing for five seconds; and quiet sitting for five seconds. Each movement was repeated after a break. Finally, the participant was asked to walk in an oval-shaped path for 40 s. To evaluate the test-retest repeatability, MIMUs and markers were detached from the participant's body and re-attached. Then, the above procedure was repeated. Hip FE/AA data were used for the proposed calibration. The knee FE/AA and quiet standing/sitting data were used to compare the repeatability of the calibration procedure proposed in the literature (Favre et al., 2009; Palermo et al., 2014) when applied to the AF definition identical to the present study.

2.4. Data analysis

2.4.1. Accuracy and repeatability analysis

To evaluate the accuracy and repeatability of the proposed functional calibration we obtained ${}_{SF}^{AF}R_{MCS}$ measured by the motion capture system during quiet standing and compared it with ${}_{SF}^{AF}R_{MIMU}$ obtained with the proposed calibration,

$$ {}_{SF}^{AF}R_{MCS} = \left({}_{AF}^{G}R_{MCS}\right)^{T} \cdot {}_{PF}^{G}R_{MCS} \cdot {}_{SF}^{PF}R, \tag{2}$$

where ${}_{SF}^{AF}R_{MCS}$ and ${}_{PF}^{G}R_{MCS}$ are the anatomical and plate frames during quiet standing, respectively. ${}_{SF}^{PF}R$ represents the constant misalignment between MIMU and plate frames due to attachment inaccuracies and calculated according to Mecheri et al. (2016). Finally, to evaluate the accuracy/repeatability of the calibration, the misalignment between the calibration matrices ${}_{SF}^{AF}R_{MIMU}$ and ${}_{SF}^{AF}R_{MCS}$ was calculated:

$$ {}_{\mathrm{Diff}}R = \left({}_{SF}^{AF}R_{MCS}\right)^{T} \cdot {}_{SF}^{AF}R_{MIMU}, \tag{3}$$

$$ \theta = \cos^{-1}\left(\frac{\mathrm{trace}({}_{\mathrm{Diff}}R) - 1}{2}\right), \tag{4}$$

The better the calibration procedure, the smaller the θ. The key feature of the proposed metric θ is that it directly measures the difference between ${}_{SF}^{AF}R_{MCS}$ and ${}_{SF}^{AF}R_{MIMU}$. Thus, there is no need for a MIMU orientation estimation, which isolates the calibration error from other sources of error. We defined the *accuracy* and *repeatability* of a calibration procedure as median and coefficient of variation (CV% = 100 × SD/mean) of metric θ among participants, respectively. The effect of the number of repetitions and test-retest repeatability on calibration accuracy/ repeatability was investigated in Supplementary Material B and C, respectively.

2.4.2. 3D hip, knee, and ankle joint angle measurement

The effect of the proposed calibration on the measured 3D hip, knee, and ankle angles during 40 s of walking in an oval-shaped path was assessed in three ways: a comparison was made between joint angles obtained by (1) AFs formed by anatomical landmarks markers (${}_{AF}^{G}R$); (2) plates frames when no calibration was applied (${}_{AF}^{G}R_{NOMIMU}$); and (3) plates frames when the proposed calibration was applied (${}_{AF}^{G}R_{MIMU}$). The differences between the joint angle time-series obtained by the three methods were measured based on offset error, root mean square error (RMSE), and range of motion (ROM), as described in Supplementary Material D.

2.4.3. Statistical analysis

To compare the proposed procedure and others, we analyzed statistically the accuracy and repeatability of the (1) calibration procedure (based on metric θ) and (2) joint kinematic measurement (based on offset error, RMSE, and ROM). We tested the normal distribution of data using the Jarque-Bera test. After confirming the equality of variance of two data sets using the Bartlett test, we compared test-retest repeatability of metric θ via paired *t*-test. The accuracy of the calibration procedures and joint kinematic measurement were compared via the Kruskal-Wallis test. Inter-participant repeatability of calibration procedures was compared via f-test on the variance of metric θ.

3. Results

Following the results presented in Supplementary Material B, we recommend five seconds of quiet standing followed by active hip FE for at least ten times as the calibration for thigh and shank MIMUs. Note that for pelvis and foot MIMUs calibration, only the quiet standing period was used. Except for the thigh MIMU, no significant difference was observed in metric θ between two repetitions in a session or between *Test* and *Retest* sessions for all MIMUs (see Supplementary Material C).

For pelvis MIMU, no significant difference was observed between the repeatability of the calibration proposed in Palermo et al. (2014) and our proposed procedure (Fig. 2 and Table 1). Our proposed procedure with hip FE resulted in highest inter-participant repeatability (CV% = 42.6%), as shown in Table 1, which is significantly more repeatable than the procedure suggested in Palermo et al. (2014). For shank MIMU, our proposed calibration obtained significantly higher inter-participant repeatability and the variance of metric θ was nearly four times smaller compared

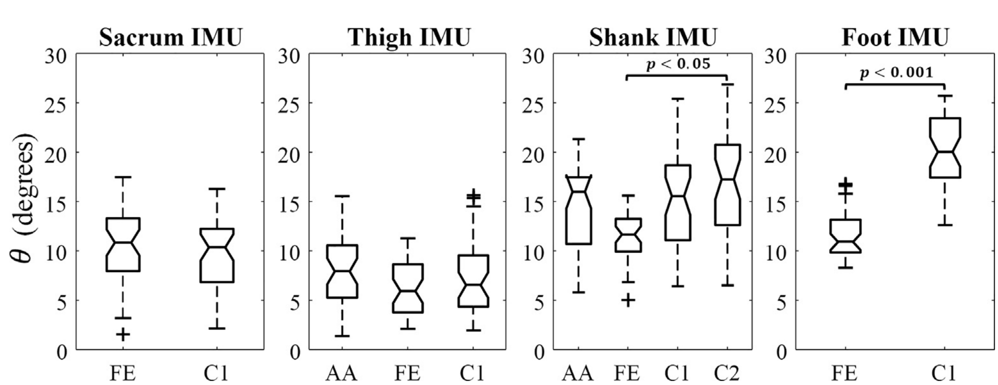

Fig. 2. The accuracy of the proposed calibration procedure compared with those proposed in Palermo et al. (2014) indicated by C1 and Favre et al. (2009) indicated by C2. Comparison of the repeatability of the procedures is not indicated in the figure.

Table 1
Inter-participant repeatability of the proposed calibration, i.e., hip flexion/extension (FE) and abduction/adduction (AA) movements, and the calibration procedures introduced in the literature: Palermo et al. (2014) indicated by C1 and Favre et al. (2009) indicated by C2. **(a)** Standard deviation (coefficient of variation%) values of metric (θ) among participants for the proposed calibration and those proposed in the literature. **(b)** Significant differences (indicated by ☆) between standard deviation values of metric (θ) for proposed calibration and those introduced in the literature.

(a)

	AA	FE	C1	C2
Pelvis	N/A	12.1 (33.7)	12.2 (36.5)	N/A
Thigh	12.0 (44.3)	7.5 (42.2)	15.2 (53.5)	N/A
Shank	20.3 (31.3)	6.0 (21.2)	23.0 (31.6)	26.5 (30.8)
Foot	N/A	5.7 (20.5)	12.4 (23.6)	N/A

(b)

	AA vs. FE	AA vs. C1	AA vs. C2	FE vs. C1	FE vs. C2
Pelvis	N/A	N/A	N/A		N/A
Thigh			N/A	☆	N/A
Shank	☆			☆	☆
Foot	N/A	N/A	N/A	☆	N/A

N/A indicates that the mentioned calibration procedure in the literature did not aim calibration of a MIMU on the segment (a) or comparison has not been performed between procedures (b).

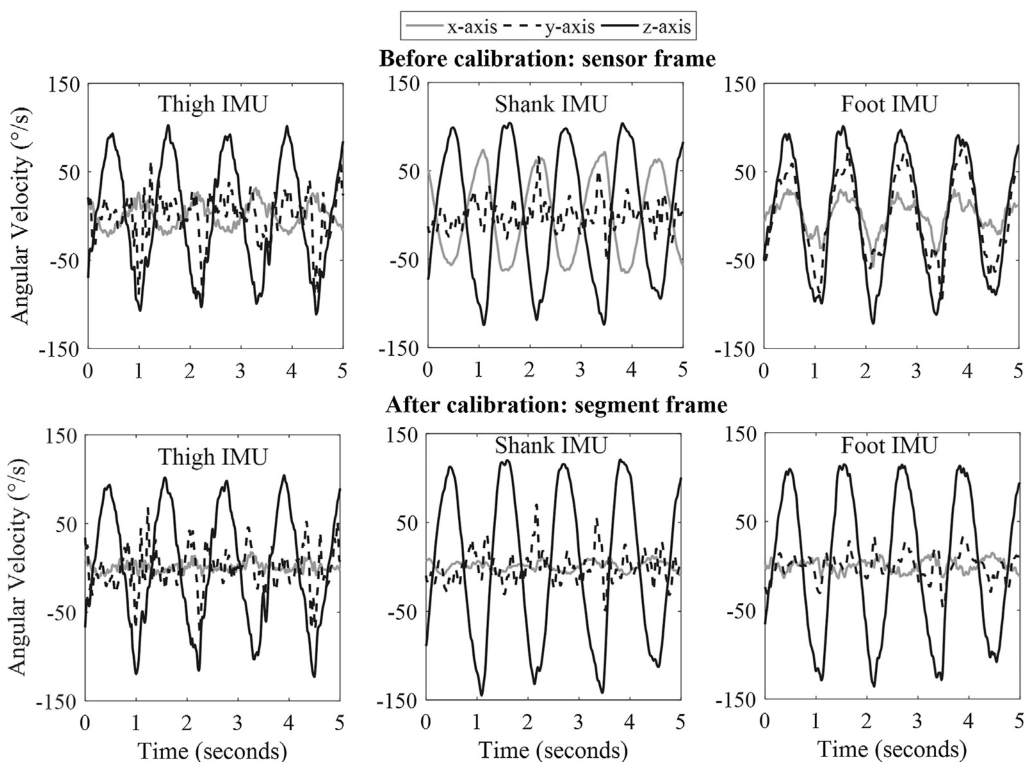

Fig. 3. 3D angular velocities of thigh, shank, and foot MIMUs during hip flexion/extension in MIMU (before calibration) and AFs (after calibration) frames for the representative participant during a representative hip flexion/extension trial.

to both (Favre et al., 2009; Palermo et al., 2014). For the foot MIMU, our proposed calibration performed significantly more repeatable ($p < 0.05$) than the method in Palermo et al. (2014).

Our proposed calibration effectively reduced the crosstalk among MIMU readouts in all MIMUs (Fig. 3). Also, using the proposed calibration procedure, the offset errors of H_{IE}, K_{AA}, K_{IE}, A_{IV}, and A_{IE} were significantly lower ($p < 0.05$) than not performing the calibration (Table 2 and Fig. 4). In addition, the proposed calibration resulted in more repeatable results for H_{AA}, H_{IE}, K_{IE}, A_{DP}, A_{IV}, and A_{IE}, indicated by the smaller standard deviation (among participants) of the offset error. Moreover, by applying the proposed calibration, K_{AA}, A_{DP}, A_{IV}, and A_{IE} angles were estimated with significantly lower RMSE than not performing the calibration. Finally, while the ROM estimation always tended to be more accurate and repeatable by applying the calibration than not performing the calibration, significant improvement was observed only for A_{IV}.

4. Discussion

This study presents an effective calibration procedure to align the MIMU frame with the AF of its corresponding segment. Among several types of hip and knee movements, the most efficient functional movement recommended by our proposed calibration was a few seconds of quiet standing followed by at least ten consecutive hip FE movements. In this procedure, MIMUs attached on the pel-

Table 2
The offset error and RMSE of the joint angle (the difference between joint angles estimated based on MIMU frame with and without calibration and the true ones obtained via AFs) and ROM of the estimated and true joint angle time-series. The results are presented as mean (standard deviation) values among participants.

	Offset error		RMSE		ROM		
	Proposed calibration	No calibration	Proposed calibration	No calibration	Proposed calibration	No calibration	Reference
H_{FE}	9.4 (4.1)*	7.0 (4.5)	3.1 (1.2)	3.0 (1.0)	48.2 (4.5)	48.6 (4.8)	45.3 (3.5)
H_{AA}	3.2 (2.0)	4.8 (3.3)‡	2.2 (0.7)	2.2 (0.6)	27.0 (4.1)	28.6 (5.1)†	18.2 (2.7)
H_{IE}	7.1 (2.9)	10.0 (5.8)*,‡	6.9 (2.4)	7.0 (2.3)	41.0 (8.3)	40.9 (10.2)	44.9 (5.0)
K_{FE}	4.7 (3.6)	4.5 (2.6)	2.7 (0.8)	2.8 (1.0)	85.0 (5.8)†	85.7 (7.3)†	76.7 (4.6)
K_{AA}	4.2 (2.8)	8.6 (4.0)*	3.6 (1.0)	6.1 (1.9)*,‡	28.0 (5.3)†	33.9 (7.1)†	10.3 (2.5)
K_{IE}	12.8 (9.4)	26.3 (13.9)*,‡	8.0 (3.3)	8.3 (3.1)	40.4 (7.9)†	45.2 (8.9)†	27.5 (4.5)
A_{DP}	2.8 (1.8)	4.8 (3.3)‡	3.2 (1.0)	5.5 (1.0)*	53.3 (13.3)†	60.4 (18.3)†	38.5 (10.2)
A_{IV}	9.4 (3.0)	23.3 (4.9)‡	2.7 (1.1)	5.7 (1.3)*	35.7 (5.3)	46.1 (9.9)†	32.0 (6.1)
A_{IE}	8.9 (5.0)	21.2 (9.9)‡	4.7 (2.0)	7.0 (2.7)*	24.7 (11.7)†	35.1 (14.7)†	16.6 (7.8)

* Indicates procedure with significantly lower accuracy (higher mean value of offset or RMS error) ($p < 0.05$).
‡ Indicates procedure with significantly lower repeatability (higher standard deviation of offset or RMS error) ($p < 0.05$).
† Indicates ROM which is significantly different from its corresponding true ROM ($p < 0.05$).

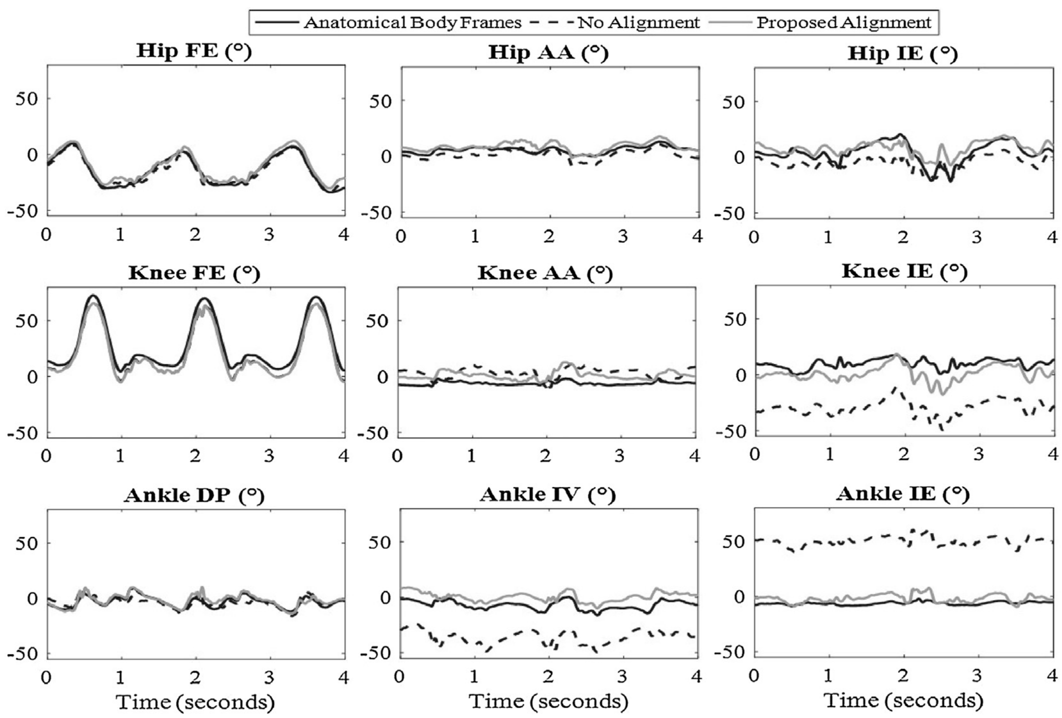

Fig. 4. 3D joint angles for the hip, knee, and ankle, estimated with and without calibration and those measured by cameras based on AFs formed by markers on anatomical landmarks for the representative participant during a representative gait trial; flexion/extension (FE), abduction/adduction (AA), and internal/external rotation (IE) for hip and knee, and dorsi/plantar flexion (DP), inversion/eversion (IV), and internal/external rotation (IE) for ankle.

vis and foot were aligned using the accelerometer readout during quiet standing, and thigh and shank MIMUs were aligned using accelerometer readout during quiet standing and gyroscope readout during hip FE.

Most of the calibration procedures in the literature rely on a single repetition of a passive or active movement or static posture (Cutti et al., 2010; Favre et al., 2009; Ligorio et al., 2017; Luinge et al., 2007; Palermo et al., 2014). A slight violation of the assumption during a single movement or posture could lead to large misalignment errors, considering the underlying assumption for calibration movements or postures, e.g., single-axis rotation of a segment during a movement or maintaining a same sagittal plane during two static postures. Our proposed procedure, on the other hand, relied on quiet standing and ten or more consecutive hip FEs, which showed high inter-participant and test-retest repeatability against the imprecision of the calibration movement.

For the shank MIMU, our proposed calibration obtained significantly smaller mean θ (an indicator of accuracy) compared to Favre et al. (2009), and for the foot MIMU compared to Palermo et al. (2014). However, the accuracy of this calibration procedure depends on the AF definition; inter-participant repeatability provides a stronger basis for comparing calibration procedures. Our proposed calibration obtained significantly higher inter-participant repeatability than those in the literature except for the pelvis MIMU (Table 1). The variability could be due to inter-participant variability of AFs as well as participants' inability to perform hip movements in a single anatomical plane. Moreover, the defined AFs based on anatomical landmarks are not fully aligned with the functional rotation planes of the joints, causing residual errors in joint angles (Table 2).

Although it was not necessary, in this study, both study coordinators tried to visually align MIMUs with AFs. Nevertheless, the offset error of the estimated joint angles was significantly reduced after calibration for all lower limb joints in frontal and transverse planes, compared to the joint angles obtained based on AFs formed by markers on anatomical landmarks (Table 2).

The proposed calibration was validated only for ten able-bodied participants and should be further validated for individuals unable to perform the proposed functional calibration. For elderly adults and those with a disability, quiet standing can be performed with the help of an auxiliary device or another person, or be substituted with sitting or lying. These possibilities should be investigated in the future.

Conflict of interest statement

None.

Acknowledgments

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jbiomech.2019.01.027.

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