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Introduction

Ankle joint kinematics assessment plays a critical role in clinics, prosthetics, and sports contexts (Akins et al., 2015; Deleu et al., 2020; Moisan et al., 2017). The ankle joint complex (AJ) is composed by the coalescence of two main joints: i) tibiotalar, formed by the tibia-fibula and the talus; ii) talocalcaneal, formed by the talus and the calcaneus. AJ movements description needs a distinction between *fundamental* and *applied* meaningful nomenclature (Neumann et al., 2017).

In the *fundamental* definition, typically applied in clinical settings, three movements are defined: i) plantarflexion-dorsiflexion (PD), occurring in the sagittal plane about a medio-lateral axis; ii) abduction-adduction (AA), occurring in the transverse plane about a vertical axis; iii) inversion-eversion (IE), occurring in the frontal plane about an anterior-posterior axis (Fig. 1a). Conversely, from the perspective of *applied* functional anatomy, the AJ motion can be described as the composition of the motions about the two skewed functional axes of the tibiotalar and talocalcaneal joints (Piazza and Lewis, 2007). Estimating these axes of rotation is a non-trivial task, being the joints involved not directly accessible (Wu et al., 2002). The combination of the motions during walking with the foot on the ground about the two axes (comprising PD, IE, and AA) is named prono-supination, according to *applied* functional anatomy nomenclature (Neumann et al., 2017). Each rotation is predominantly expressed by a joint: PD at tibiotalar level and IE and AA at talocalcaneal level (Lundgren et al., 2008; Siegler et al., 1988). Given the latter premises, the movement occurring about the tibiotalar joint axis can be associated with the PD angle.

Ankle joint kinematics can be consistently estimated through stereophotogrammetric systems (SP), based on several biomechanical models able to satisfactorily map the AJ complexity (Leardini et al., 2019). Several anatomical landmarks (ALs) can be identified and used in the definition of joint coordinate systems (JCS) describing AJ anatomy and behavior. However, the complexity of the anatomical coordinate system (ACS) identification should be selected according to a specific aim, spanning from simply describing the main joint movement as the rotation about a single axis (e.g. isolating one specific DOF such as PD), up to the 3-dimensional description of the main foot bones movements. The latter may be necessary to properly describe pathological gait which combines movements about all planes of motion. Nonetheless, SP are limited by high costs, minimal portability, fixed acquisition volume, and necessity for an experienced technician (van der Kruk and Reijne, 2018). The AJ analysis may be further limited by the difficulty of tracking several markers onto small body segments.

FIG1

In the past few decades, wearable magneto-inertial measurement units (MIMUs), including three-axial accelerometers, gyroscopes and magnetometers, emerged as a reliable alternative to SP for human movement analysis (Iosa et al., 2016; Picerno, 2017). The orientation of multiple MIMUs can be estimated and expressed in a common coordinate system (CS) by using sensor fusion filters (Kok et al., 2017; Caruso et al., 2021). Hence, joint kinematics can be assessed by rigidly fixing two MIMUs on two adjacent body segments, and by computing the orientation of the distal segment relative to the proximal one (Picerno, 2017; Weygers et al., 2020). To obtain an anatomically meaningful description of these relative orientations, rotations should be expressed about anatomically-derived rotation axes, which can be embedded in the ACS of the proximal and distal segments (Camomilla et al., 2018; Cereatti et al., 2017; Wu et al., 2002).

With specific reference to the ACS definition using MIMUs, several strategies have been proposed (Picerno, 2017; Weygers et al., 2020). In line with the SP approach, some exploited

ALs to obtain the direction of relevant anatomical axes (Picerno et al., 2019, 2008): this approach requires an experienced operator and an *ad-hoc* calliper and it cannot rely on internal ALs resulting from averaging external ones. Others proposed to manually align a sensor axis to the joint axis about which the prevalent rotation is observed (Bouvier et al., 2015; Choi et al., 2018; Kun Liu et al., 2009; Šlajpah et al., 2014). This approach is not adequate for the AJ, due to foot anatomy not allowing to align any sensor axis to meaningful anatomical axes, and since rotations are entangled one another.

As an alternative, functional calibration (FC) can be adopted, requiring the execution of repeatable movements about the main axes of rotation of the joint under analysis (Favre et al., 2009; O'Donovan et al., 2007). Such technique was successfully applied to different human joints to identify subject-specific joint model parameters, such as the location of the shoulder (Crabolu et al., 2017) and hip joint center (Crabolu et al., 2016); one (Ligorio et al., 2017; Wells et al., 2019) or two axes (Laidig et al., 2017) for the elbow and one for the knee (Favre et al., 2009).

Only a few studies identified the tibiotalar axis using a FC approach (Pacher et al., 2020): some computed it directly from walking (Seel et al., 2014), others exploited functional movements related to other joints to estimate it (Cutti et al., 2010; Nazarahari and Rouhani, 2019; O'Donovan et al., 2007). Only two exploited *ad-hoc* ankle functional movements, either performing a squat test (Zhou et al., 2018) or an active PD movement (Meng et al., 2019). However, both studies opted for an active movement under the assumption that, during the calibration, the ankle moves predominantly as if it had only one DOF, subjecting the outcomes to the potential variability of uncontrolled functional movements. Moreover, active movements narrow protocol applicability to healthy individuals only, excluding clinical conditions limiting AJ mobility. Nonetheless, none tested calibration repeatability.

To overcome these limitations, an anatomical calibration protocol is proposed, based on a combination of passive functional movements and static acquisitions, aiming to estimate the main tibiotalar axis. Repeatability and reliability of this protocol were assessed on the PD angle computed using this protocol through the metrics proposed by Schwartz et al. (2004) on ten participants undergoing instrumented gait analysis through both SP and MIMUs, whose anatomical FC was performed by three different operators. The anatomical calibration procedure, anatomical coordinate systems, and kinematic model were chosen to be the same for SP and MIMUs with the aim of evaluating the impact of the use of the latter equipment in terms of reliability and repeatability, thus excluding other sources of disagreement (e.g., different ACSs or kinematic models).

Materials and methods

Ankle joint coordinate system

The proposed JCS is built on the definition of the ACSs for foot and shank segments having the medial-lateral axis in common. The proposed JCS finds its rationale on two main modelling choices:

1. the main AJ axis of rotation is coincident with the main tibiotalar joint axis of rotation, as it involves mainly PD. It is identified through repeated, passive PD movements of the foot;
2. the foot and shank ACSs are orthogonal (right-handed). For this purpose, two auxiliary axes are identified through orthostatic posture trials, and used as representing the shank vertical) and foot longitudinal axes.

The main AJ axis of rotation is used to identify both the shank and foot medial-lateral axis, pointing rightwards. Secondly, the shank anterior-posterior axis is chosen to be perpendicular to the plane identified by shank medial-lateral and shank auxiliary axes, pointing forward. Similarly, the cranio-caudal foot axis is chosen to be perpendicular to the plane identified by the foot medial-lateral axis and the foot auxiliary axis, pointing upward. Finally, the remaining axes of each ACSs are obtained according to the right-hand rule. The ACSs are then used to obtain PD from the JCS as described in the Data Processing section.

Shank ACS is built such that ${}^{T,SH}R_{A,SH} = [X^{SH}, Y^{SH}, Z^{SH}]$, where T and A denote the segment technical and anatomical CSs, respectively (Cappozzo et al., 1995), the notation ${}^{CS1}R_{CS2}$ indicates a rotation matrix expressing the orientation of CS_2 relative to CS_1, whose components are computed as:

$$ {}^{T,SH}R_{A,SH}\ \{Z^{SH} = a^F \qquad X^{SH} = Z^{SH} \times a^V \quad Y^{SH} = Z^{SH} \times X^{SH} \tag{1} $$

Foot ACS, ${}^{T,FT}R_{A,FT} = [X^{FT}, Y^{FT}, Z^{FT}]$, is built such that:

$$ {}^{T,FT}R_{A,FT}\ \{Z^{FT} = a^F \qquad Y^{FT} = a^L \times Z^{FT} \quad X^{FT} = Y^{FT} \times Z^{FT} \tag{2} $$

An illustration of the general ACSs created through Eq. (1) and (2) is presented in Fig. 1b-c.

Repeatability and reliability study

Given the uncertainty associated with the tibiotalar axis identification, the extrinsic and intrinsic factors contributing to variability, i.e. the operator and the subject respectively, were evaluated. Repeatability was assessed from the repeated calibrations of each specific operator and from repeated gait measures of each subject (operator and subject repeatability), while reliability was assessed relative to: i) different operators, who repeatedly performed the calibration measures (operator reliability), and ii) different measurement systems, based on the comparison of the MIMU-derived kinematic traces with the SP-derived ones (instrumental reliability).

Ten healthy volunteers (6M, 4F; age = 27.1 ± 3.0 years; stature = 1.73 ± 0.08 m; mass = 66.4 ± 10.1 kg) were recruited, each signing an informed consent. The study was approved by the Internal Review Board of the University of Rome “Foro Italico” (CAR 79/2021). A seven cameras SP system (Vicon Bonita, Vicon, Oxford, UK; sampling rate = 100 samples/s) and three MIMUs (Vicon Blue Trident, Vicon, Oxford, UK; accelerometer and gyroscope sampling rate = 1125 samples/s, magnetometer sampling rate = 100 samples/s; full scale range: accelerometer = ± 16 g, gyroscope = ± 2000 deg/s, magnetometer = ± 4900 µT) were used. Bias removal and sensor recalibration procedures were performed for all MIMUs prior to each experimental session with *ad-hoc* acquisitions (Bergamini et al., 2014). The magnetic field vector norm was checked over the capture volume prior each session, searching for possible ferromagnetic disturbances that would have had affected sensors orientation (Bergamini et al., 2014). MIMU and SP systems were radio synchronized through the manufacturer's software (Vicon Nexus 2.9).

FIG2

Two plastic plaques equipped with four retro-reflective markers were positioned at participants shank and foot (Fig. 2). A MIMU was rigidly attached to each plaque. Plaques were secured to shank and shoe with adhesive tape to minimize soft tissue artefacts due to skin sliding and wobbling. A wooden plate equipped with a MIMU and four markers was used during the calibration procedures (Fig. 2).

Three operators were recruited to perform the anatomical calibration, each performing three times:

i. *orthostatic posture calibration*: with the participant standing in orthostatic posture, to estimate shank vertical axis and foot longitudinal axis. The limb under analysis had the medial portion of the foot aligned with the instrumented wooden plate (Fig. 2);
ii. *ankle functional calibration*: with the participant sitting on a chair, the operator performed 10 passive PDs, to estimate the tibiotalar axis (Fig. 3).

After the anatomical calibration procedure, each participant performed three rectilinear gait trials at self-selected speed.

Data processing

Time-invariant orientation of the ACSs relative to the sensor technical CS was obtained for both shank and foot from the anatomical calibration (${}^{T,SH}R_{A,SH}$ and ${}^{T,FT}R_{A,FT}$).

First, to use the same FC procedure for both systems, the SP-computed foot technical CS, ${}^{G}R_{T,FT}$, was converted to its Euler's angles representation. Hence, angles were numerically differentiated, so that the foot angular velocity, $\boldsymbol{\omega}(t) = [\omega_x(t), \omega_y(t), \omega_z(t)]^T$ could be computed. Such an angular velocity was compatible with the one directly measured via foot-mounted MIMU. Thus, the same procedure applied for both systems:

1. A threshold value, ω_{thr}, was computed, corresponding to the 40% of the maximum value $\omega_z(t)$ assumed during the passive PD;
2. All $\boldsymbol{\omega}(t_i) : \omega_z(t_i) > \omega_{thr}$ were chosen. Values of $\omega(t)$ not satisfying such a condition were not considered;
3. All $\boldsymbol{\omega}$(ti) above threshold were normalized such that $\boldsymbol{\omega}(t_i)_{norm} = \boldsymbol{\omega}(t_i) / \| \boldsymbol{\omega}(t_i) \|$;
4. Their mean value was computed and normalized again, as above.

The normalized mean value was chosen to be the main AJ axis of rotation, denoted as a^F (with $a^F \triangleq Z^{SH} \triangleq Z^{FT}$).

Orthostatic posture calibration data were processed to obtain the shank vertical axis (a^V) as the mean accelerometer of the shank MIMU, and the foot longitudinal axis (a^L) as the mean longitudinal axis of the MIMU placed on the wooden plate. For this static trial, CSs were estimated using a TRIAD approach (Shuster and Oh, 1981) starting from accelerometer and magnetometer observations, thus following the procedure proposed in Valenti et al. (2015). All axes' directions were represented as unit vectors.

An indirect Kalman filter sensor fusion algorithm was used for processing foot- and shank-mounted measures during gait trials (The Mathworks Team, 2022). The algorithm provided the orientation of the technical CS relative to the global CS by fusing accelerometer, gyroscope, and magnetometer measures, for both shank and foot MIMUs, denoted as ${}^{G}R^{(i)}_{T,SH}$ and ${}^{G}R^{(i)}_{T,FT}$, respectively. ACSs orientation relative to the global CS were obtained:

$${}^{G}R_{A,SH}^{(i)} = {}^{G}R_{T,SH}^{(i)} \cdot {}^{T,SH}R_{A,SH} \qquad i = 1,\ldots,K$$	(3)
$${}^{G}R_{A,FT}^{(i)} = {}^{G}R_{T,FT}^{(i)} \cdot {}^{T,FT}R_{A,FT} \qquad i = 1,\ldots,K$$	(4)

where (i) denotes the *i*-th time instant and K the total number of samples.

The same rotation matrices were obtained from the SP data, using a least square pose estimator on each marker cluster (Cappozzo et al., 1997).

Finally, the PD angle during gait was computed exploiting ${}^{G}R_{A,SH}$ and ${}^{G}R_{A,FT}$ according to Grood and Suntay (1983). For the sake of clarity, the unit vector nomenclature was maintained in its original form. The JCS was chosen considering: e_1 as the shank medial-lateral direction ($e_1 \triangleq a^F \triangleq Z^{SH} \triangleq Z^{FT}$); e_3 as the foot cranio-caudal direction ($e_3 \triangleq Y^{FT}$); e_2 (*floating* axis) as the cross product of the latter ($e_2 = e_3 \times e_1$).

Statistical analysis

Operator and subject repeatability and reliability were evaluated following what proposed in (Schwartz et al., 2004), identified by the variable σ^L, where L is the considered variability level. Let L be a variability level for the kinematic variable Φ and a number P of trials of Φ, such that each trial is denoted as $\Phi_p(t)$, t = 1,...,t_f.

1. Considering all the P trials, compute the mean kinematic trace for the level L:

$$\underline{\Phi}^L(t) = \frac{1}{P}\sum_{p=1}^{P} \Phi_p(t) \qquad t = 1,\ldots,t_f$$	(5)

2. For all the P trials, and for all time instants, compute the deviation from the mean trace:

$$\Delta\Phi_p = \frac{1}{t_f}\sum_{i=1}^{t_f} \quad [\Phi_p(i) - \underline{\Phi}^L(i)] \tag{6}$$

3. The variability of the level L is expressed in terms of standard error, based on the obtained P (scalar) deviations $\Delta\Phi^L = \{\Delta\Phi_1,...,\Delta\Phi_P\}$:

$$\sigma_\Phi^L = \sqrt{\frac{1}{P-1}\sum_{p=1}^{P} \quad [\Delta\Phi_p]^2} \tag{7}$$

where σ^L_Φ is the standard deviation of the level deviations.

FIG3

Four variability levels were evaluated: intra-operator ($\sigma^{i,Okj}$) and intra-subject ($\sigma^{i,Sk}$), accounting for repeatability; inter-operator ($\sigma^{I,gkj}$), and inter-subject (σ^I), accounting for reliability. The superscripts i and I indicate an intra- and inter- analysis, respectively; P assumes different values according to the level it refers to: for intra-operator and intra-subject repeatability P = 3; for inter-operator reliability P = 9; for inter-subject reliability P = 270. The superscript O_{kj} and g_{kj} refer to the *j*-th operator and gait (j = 1,...,3), respectively; the superscript S_k refers to the *k*-th subject (k = 1,...,10). For the sake of clarity, no subscript was used to indicate the kinematic variable, since only PD was analyzed. Furthermore, the intraclass correlation coefficient (ICC) was used as an additional measure for evaluating intra-operator repeatability (ICC 2,1) and inter-operator reliability (ICC 2,k). The ICC values were computed and evaluated as suggested in Koo et al. (2016):

ICC < 0.5 = poor reliability; 0.5 ≤ ICC < 0.7 = moderate reliability; 0.7 ≤ ICC < 0.9 = good reliability; ICC ≥ 0.9 = excellent reliability. Moreover, to rate the importance of experimental errors, an extrinsic-to-intrinsic ratio (EIR) between inter-operator and intra-subject variability was computed to measure the percent influence of the variability introduced by the operators (extrinsic) against the one introduced by the subject (intrinsic):

$$EIR^{S_k,g_j} = \frac{\sigma^{I,g_{kj}}}{\sigma^{i,S_k}} \quad (8)$$

A schematic description of the procedure is provided in Fig. 4.

Instrumental reliability (commonly referred to as agreement in literature (Bartlett and Frost, 2008)) of the MIMU implementation was also assessed by comparing each kinematic trace computed through MIMU with the corresponding SP-measured one. To this purpose, reliability was evaluated through root mean square difference (RMSD), offset (PD_{offset}), and strength of the linear relationship between each couple of kinematic traces (R^2). The latter two variables were computed through the linear fit method (Di Marco et al., 2018; Iosa et al., 2014). Such a method assessed the consistency of a set of time-normalized curves. The hypothesis of correlation between time instants was ensured, as the two systems were synchronized through the software provided by the manufacturer.

Results

FIG4-Table1

A total of 270 gait cycles were analyzed. The average range of motion (± SD) computed on the 270 gait cycles was 30.3 ± 5.8 deg and 32.5 ± 5.8 deg for SP and MIMU systems, respectively. Operator and subject repeatability and reliability were evaluated at four levels for MIMU-derived kinematic traces and is presented for a subject representative of the population, along with the variability of the entire population, in Fig. 5. The 270 trials showed an overall inter-subject reliability σ^{I} = 4.8 deg, with a mean intra-subject repeatability of $\sigma^{i,S}$ = 2.3 ± 0.6 deg, over the 10 subjects. Inter-operator reliability analysis showed that operators affected the measures by a mean $\sigma^{I,G}$ = 0.8 ± 0.5 deg ($ICC^{I,G}$ = 0.999), over the 10 subjects. The mean intra-operator repeatability, measured over the 10 subjects, were $\sigma^{i,O1}$ = 0.4 ± 0.3 deg ($ICC^{I,O1}$ = 0.996), $\sigma^{i,O2}$ = 0.5 ± 0.6 deg ($ICC^{I,O2}$ = 0.991), and $\sigma^{i,O3}$ = 0.3 ± 0.2 deg ($ICC^{I,O3}$ = 0.998) for operator one, two, and three, respectively. ICC assessment analysis results are presented in Table 2. An overview of operators' repeatability and reliability analysis is presented in Fig. 6. The EIR was computed for each subject and each gait, showing an overall mean value of 32% (Table 1).

FIG5-6

Instrumental reliability analysis showed that the MIMU-derived kinematics traces differed (± SD) from the SP-derived ones by an overall mean RMSD = 3.0 ± 1.3 deg, with a mean offset of PD_{offset} = 9.4 ± 8.4 deg. A graphical example of the latter analysis is reported in Fig. 7, depicting a gait cycle of a subject representative of the population and its RMSD varying throughout the gait cycle. Finally, the mean strength of linear relationship (± SD) between the kinematic traces of the two systems was $R^2 = 0.88 \pm 0.08$, satisfying the condition for linearity ($R^2 > 0.5$). Results are detailed for each subject in Table 1.

Discussion

This study proposed an anatomically consistent description of the ankle PD angle based on the use of MIMUs. The experimental protocol consists of two anatomical calibrations: one estimates the direction of the anatomical tibiotalar axis through a functional movement; the other estimates shank and foot auxiliary axes through an orthostatic posture. The protocol proved to have a small extrinsic variability compared to the intra-subject intrinsic one. It showed both good repeatability of the repeated measures of each operator and good reliability relative to: i) different operators, who repeatedly performed the FC measures; ii) different instrumentation, based on the comparison of MIMU- and SP-derived kinematics.

The intrinsic mean intra-subject repeatability ($\sigma^{i,S}$ = 2.3 ± 0.6 deg), accounting for the differences within the three gait trials, had a limited amplitude compared to the trial ROM (7.3 ± 2.4%). Intrinsic variability of the ankle kinematics, assessed in terms of stride-to-stride mean SD over the entire gait cycle (1.9 deg), is in line with previous literature assessing it over the stance phase (1.4 deg - Dingwell et al., 2001). Nevertheless, this variability proved to be more impactful than the extrinsic factors: operator repeatability ($\sigma^{i,O1}$ = 0.4 ± 0.3 deg, $\sigma^{i,O2}$ = 0.5 ± 0.6 deg, and $\sigma^{i,O3}$ = 0.3 ± 0.2 deg) and reliability ($\sigma^{I,G}$ = 0.8 ± 0.5 deg) represented the 1.3 ± 1.1% and 2.3 ± 1.4% of the relevant ankle ROM, respectively. This is corroborated by the EIR index, ranging from 8% to 56% (32% ± 17%), showing a wider intrinsic gait variability than that introduced by the operators. While it can be speculated that the degree of experience of the operators could influence variability when performing the anatomical FC procedure, it has to be said that the operators recruited in the current study had little theoretical background about ankle functional anatomy. Furthermore, as ICC shows ($ICC^{I,G}$ = 0.999), an excellent inter-assessor agreement was found, suggesting that basic knowledge of ankle functional anatomy is sufficient to perform a repeatable and reliable anatomical FC procedure following the proposed protocol. The calibration procedure introduced a low variability, possibly thanks to the fact that the tibiotalar axis was estimated through passive movements performed by an external operator, thus limiting potential joint movements other than PD.

Instrumental reliability analysis, comparing SP- and MIMU-derived kinematics, identified the offset as the wider difference (PD_{offset} = 9.4 ± 8.4 deg), whereas the curves had a smaller RMSD (3.0 ± 1.3 deg) and a linear relationship with a very high strength (R^2 = 0.88 ± 0.08) (Di Marco et al., 2018; Iosa et al., 2014). The RMSD values are in accordance with the ones reported by others (Bergmann et al., 2009; Cloete and Scheffer, 2008; Lebel et al., 2017; Rouhani et al., 2012; Saito and Watanabe, 2011; Zhang et al., 2013; Meng et al., 2019) accounting for instrumental reliability of MIMU/SP systems during gait (average RMSD of about 5 degrees among studies). The relatively large amount of offset among the systems, usually not reported in other studies or simply removed, can be attributed to issues in sensor orientation estimation. Current results must be interpreted in the following framework: magnetic field disturbances could play a critical role in MIMUs orientation estimates. For this reason, the magnetic disturbances presence was checked prior each experimental session throughout the capture volume. If checking is not possible it would be beneficial to carry out the orthostatic posture acquisition at least half a meter from the ground (Bachmann et al., 2004).

Furthermore, the software used could not record SP and MIMU systems at the same sampling frequency. To compare the systems, MIMU data had to be downsampled to match the SP sampling frequency (100 samples/s). Hence, the RMSD could have grown due to misalignment brought by such a procedure.

Finally, the self-selected walking speed may influence the MIMU-PD estimates, since increasing velocity negatively affects kinematic reliability (Lebel et al., 2017; Meng et al., 2019), possibly due to an increase in soft tissue deformation and wobbling (Forner-Cordero et al., 2008; Mascia and Camomilla, 2021; Scalera et al., 2021). Moreover, the current dimension and mass of wearable MIMUs candidate them as potential amplifiers of the rigid component of soft tissue artifact affecting the pose estimate of the rigid body segments involved (Dumas et al., 2015). However, these aspects did not affect current results as sensors were fixed within a rigid plastic cluster equipped with markers.

Although not critical when focusing on the PD angle only, it must be highlighted that the Grood & Suntay convention, developed for the knee, can be interpreted in two different ways when used for the ankle. In the original model, e_3 was defined as the longitudinal axis of the distal segment, corresponding to the cranial-caudal shank axis. Since the longitudinal axis of the foot corresponds to its anterior-posterior axis, one can chose e_3 as the vertical axis of the foot, in line with Grood and Suntay (1983) and the ISB standard (Leardini et al., 2019; Wu et al., 2002) or the anterior-posterior foot axis, corresponding to the segment longitudinal axis (Stebbins et al., 2006). In the present study the ankle JCS was defined according to the first approach in agreement with the current standard. The definition of e_3 and the resulting floating axis, mainly influencing ankle AA and IE angles estimates, minimally affects the PD angle under analysis in this paper. Further speculation is required if using the proposed model for AA and IE estimates.

The recommendation is to include both a proper calibration for MIMUs (Bergamini et al., 2014) and an optimal pose estimator for SP (Cappozzo et al., 1997), as they are critical steps in such an experimental design. Instrumental reliability distances computed as RMSD were mainly due to the offset which, presumably, was introduced by sensor fusion. With due caution, the protocol can be considered repeatable and reliable, and the kinematics traces computed through MIMU consistent with the SP ones.

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