Which functional movements for sensor-to-segment calibration for lower-limb movement analysis with inertial sensors?

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1. Introduction

If human motion analysis in laboratory can be considered as matured regarding the extensive research that has been performed in terms of technology and methodology, it is not the case for human motion analysis based on inertial sensors.

Basically, for 3D movement analysis, angular velocities and linear accelerations measured by respectively the 3 gyroscopes and the 3 accelerometers present in one 3D-Inertial Measurement Unit (IMU) are sent to a data fusion algorithm in order to obtain orientation and, sometimes, also position (see Picerno 2017 for a review). Several challenges remain to be solved for this technology to be really effective and spread and this includes the sensor-to-segment calibration.

Indeed, to estimate joint kinematics, the rotational matrix that enables to obtain the body segment referential frame orientation from that of the sensor is required for each sensor. Different procedures have been proposed in the literature (Picerno 2017). Some of them use static postures whereas others use devices to locate anatomical landmarks required to define segment axes relatively to the sensor referential frame. Unfortunately, these approaches are limited in terms of accuracy or require additional equipment.

With the “functional approach”, specific movement performed at a joint is used to define a segment axis assuming that the angular velocity vector is aligned with the segment axis around which the movement is performed. Even if not yet demonstrated, this functional approach seems to provide the best ratio between time, ease, and accuracy. However, none of the functional approaches is currently recognized as a “gold standard”. These procedures should then be more thoroughly investigated in order to define their advantages and drawbacks.

We propose in the present study to investigate the calibration movements for lower-limbs sensor-to-segment calibration. Indeed, the accuracy of the functional approach is limited by the precision with which the subjects can perform the motions, which is of particular importance to define axes in segment such as the thigh segment.

In the present study, the segment axes will be defined with angular velocity vectors, not measured by inertial sensors but deduced from markers tracked by an optoelectronical system. The segment axes will then be confronted with those obtained by validated functional approach and model that have been proposed in traditional 3D motion analysis based on optoelectronical systems. To consider kinematics measures, models and methods based on optoelectronical systems as the gold standard enables to limit uncertainties due to lack of studies on human movement analysis based on inertial sensors (such as sensor locations for instance).

2. Methods

2.1. Participants

12 subjects recruited in the institute took part in this study. They were aged between 22 to 60 years, their weight was 78.5 ± 22.2 kg, their height 175 ± 10.1 cm. They all provided their informed consent.

2.2. Protocol

32 reflective markers were placed on the subject at location limiting soft tissue artefact on segment coordinate frame definition. The marker positions were recorded by 20 cameras cadenced at 200 Hz.

Table 1 presents the calibration movements tested and the segment axis that they define. Each movement was repeated 6 times. Technical coordinate frames were determined for each segment based on markers located on the segment. Quaternions corresponding to orientation of the technical coordinate frames in the global coordinate system were then computed. From these quaternions, angular velocity vectors were obtained following the formula: \( \omega = 2q^* \)
where \( \omega \) refers to the angular velocity, \( \dot{q} \) designed the first
derivative of the quaternion and \( q^* \) its conjugate.

Segment axis was then defined as the mean unit vector
for which angular velocity was greater than 10% of the
peak angular velocity.

The “gold standard” flexion/extension axis for the knee
joint and planta/dorsiflexion axis of the ankle joint were
obtained thanks to the functional method SARA (Ehrig
et al. 2007). The hip joint centre was defined using the
method described in (Halvorsen et al. 2005). Finally, the
longitudinal segment axes were defined according to ISB
recommendations.

To compare the different calibration movements, the
angle existing between the segment axis obtained through the
functional approach mimicking the one that could be applied
with inertial sensors and the “gold standard” axes obtained
with traditional methods based on optoelectronical systems.

An ANOVA for repeated measures was then used to
compare these error angles obtained with the different
calibration movements.

### 3. Results and discussion

Except for the planta/dorsiflexion flexion axis for which
the axis obtained with the squat calibrating movement was
significantly more aligned with the “gold standard” axis
\( p<0.05 \), no difference was found between the calibrating
movements.

One could notice that the hip abduction/adduction axes
obtained by the two functional calibration movements
tested deviate by more than 20° from the gold standard
axis. This means that these two calibration movements
weren’t adequate to provoke isolated abduction/adduction
movement around the hip joint.

### 4. Conclusions

This preliminary study proposed to investigate the func-
tional calibration movements that could be used to per-
form sensor-to-segment calibration. According to the
results, calibration movements don’t significantly affect
the functional axes obtained at least in subjects that hav-
’en any lower-extremity dysfunction. However, it seems
that for the thigh, segment coordinate system should be
defined based on the flexion/extension and on the seg-
ment longitudinal axis. Moreover, squat movement–even
if not statistically significant–seems to provide the best
results to calibrate flexion/extension axes at the hip, knee
and ankle joint.

### References

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