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Xsens DOT Wearable Sensor Platform White Paper

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ABSTRACT The Xsens DOT Wearable Sensor platform is the new generation of cost efficient inertial motion trackers featuring lightweight design, Bluetooth Low energy (BLE) connectivity and robust sensor fusion algorithms to provide accurate data for human movement applications. A Software Development Kit (SDK) is provided to facilitate the development of mobile applications based on the available output data, thereby allowing developers to easily integrate the Xsens DOT into a wide range of solutions. Robust algorithms such as Strap Down Integration (SDI) and the sensor fusion framework Xsens Kalman Filter (XKF) Core; run on-board the Xsens DOT to provide the highest level of accuracy in orientation estimates and to minimize the effects of magnetic distortion. XKF Core combined with robust synchronization processes therefore allow real-time and offline analysis of human kinematics with single or multiple body-mounted motion trackers. The combined information of multiple trackers is perfectly suited for solutions that aim to provide biomechanical analysis in their end product. Biomechanical parameters such as joint angles play a key role in human movement analysis both in rehabilitation and sport applications. This white paper describes the key characteristics of the Xsens DOT wearable sensor platform and provides a performance analysis of the Xsens DOT used in a multi sensor set-up to calculate the knee joint angle. Overall, the analysis confirms that the Xsens DOT wearable sensor platform enables reliable and accurate results in the outputs of these joint angles.

INDEX TERMS wearables, inertial measurement units, mobile applications, human movement analysis

I. INTRODUCTION

HUMAN motion capture as the name suggests, involves any method of capturing motion for the purpose of human movement analysis. Such analyses allow researchers and practitioners to cover a range of applications, spanning from medical, sports, ergonomics, industrial and entertainment [1]–[6]. Methods of motion capture encompass both visual and optical methods, as well as sensor-based methods. Optical motion capture through active or passive based marker systems, is considered the gold standard, due to its high degree of precision and accuracy of position measurement [1], [7], [8], although inertial systems may equal or surpass them in certain applications [9], [10]. Besides being rivalled in accuracy, optical motion capture suffers from several drawbacks, namely being restricted to laboratory environments, long set-up and calibration times to ensure missing trajectories do not occur, as well as long processing times, that do not always prevent marker occlusion. These drawbacks prevent its adoption in many real-life and outdoor applications. As an alternative solution to optical motion tracking systems, inertial measurements units (IMUs) rose in popularity in the past two decades [11]–[13]. Typically, IMUs contain MEMS-type gyroscopes, accelerometers and magnetometers. These individual sensor signals are fused through a statistical estimation framework to obtain a 3D orientation. Despite their small size and applicability in almost any environment, such devices also encounter several technical challenges.

Magnetic disturbances are one of the main sources of error depending highly on the environment of use. Ferromagnetic objects located in close proximity can create a non-homogeneous local magnetic field, which influences the heading of the sensor. In addition to inertial motion tracking performance, reliable, universally wireless connectivity is a requirement for such devices, as they provide integral information to the internet of moving things. Furthermore, low power consumption and long battery life requirements also have to be met in order to provide stand-alone measurements

FIGURE 1. 5 Xsens DOTs and their charging case

for applications ranging from a few minutes of a sprint session, up to tracking the full-length of a marathon race; as well as lasting sufficient time frames for practitioners to perform analytical work across the space of several hours.

Xsens DOT is a state-of-the-art development platform for the analysis and reporting of human kinematics that handles many of the technical challenges that are encountered across wireless motion sensor applications. The Xsens DOT is a lightweight and water-resistant wireless motion tracker that features on-board orientation estimation, with connectivity to mobile devices through Bluetooth Low Energy (BLE), guaranteeing low power consumption and extended battery life. The platform features high-accuracy wearable inertial sensors, along with an easy-to-integrate Software Development Kit (SDK), with community support from Xsens experts. This platform allows precision human motion tracking to take place for a variety of applications and provides solutions to many markets, with sport performances analysis and health rehabilitation being its primary focus.

This whitepaper starts out by describing the DOT sensor platform in section II. This section provides details on the hardware, companion-software and sensor outputs of the Xsens DOT. In section III the different parts of the signal processing pipeline are laid out, from raw signal to filter output for a single DOT. The combination of DOTs in a multi-sensor set-up is described in section IV, which features also some basic descriptions of biomechanical measurements. Finally, the DOTs are put to the test in section V. The performance of the DOTs in gait measurements is studied by comparing it directly to Xsens MVN.

II. XSENS DOT WEARABLE SENSOR PLATFORM

A. XSENS DOT HARDWARE

1) Hardware characteristics and Sensor components

The Xsens DOT lightweight design features an IMU with a package size of $36.30 \times 30.35 \times 10.80\,\mathrm{mm}$ and a weight of $11.2\,\mathrm{g}$. Xsens DOTs, including the charger, are displayed in figure 1. The Xsens DOT is an IP68-certified water-resistant tracker which includes an internal storage of 64MB and a battery capacity of $70\,\mathrm{mA\,h}$ allowing up to $12\,\mathrm{h}$ of on-board recorded data storage.

For motion tracking, the device is equipped with inertial and magnetic sensor components, namely a 3D rate gyroscope, a 3D accelerometer and a 3D magnetometer.
The 3D gyroscope is the inertial sensor that measure the rate of turn. Numerical integration of gyroscope signals over time can be used to derive orientation. However, as sensors contain measurement noise and bias, solely relying on this approach results in orientation drift, with errors in the estimates increasing with time.
The 3D accelerometer is the inertial sensor that tracks proper linear acceleration. At rest, the measured signal equals the gravitational acceleration, which can be used as a stabilization reference for pitch and roll components.
Finally, the 3D magnetometer senses the strength and direction of the surrounding magnetic field. Magnetic field information allows the sensor to establish the orientation in space, much like the workings of a compass needle.

The output provided by these three main components is then fed into the Xsens DOT signal processing pipeline. Two main algorithms run on-board the Xsens DOT motion tracker; the Strap-Down Integration (SDI) [14] and the Xsens Kalman Filter (XKF) Core. To put it briefly, the former takes in the high-rate calibrated measurements of the gyroscope and accelerometer, integrates them, and outputs measurement increments at a lower rate of $60\,\mathrm{Hz}$ or $120\,\mathrm{Hz}$ without compromising the measurement quality. This output of the SDI, along with the calibrated magnetometer data serve as input to the XKF Core algorithm that produces accurate estimates of orientation and free acceleration in real time. The inertial and orientation data are then either transmitted to an external device via the on-board BLE module, or stored locally in the memory. The algorithms running on the Xsens DOT will be explained in further detail in Sec. III.

2) User Output Data

Before describing the output data, it is prudent to present the types of reference systems used in this white paper. Data shall be expressed in the sensor coordinate system (S), and in the local earth-fixed reference coordinate system (L). The sensor coordinate system (S) is a right-handed Cartesian coordinate system that is body-fixed to the sensor. Figure 2 depicts the sensor coordinate system on DOT, using small x, y, and z.
The local earth-fixed reference coordinate system (L) is defined as a right-handed Cartesian coordinate system with:

- X positive to the East (E).
- Y positive to the North (N).
- Z positive when pointing up (U)

This coordinate system is known as East-North-Up (ENU) and is the standard in inertial navigation for aviation and geodetic applications. With the default ENU coordinate system, Xsens yaw output is defined as the angle between East (X) and the horizontal projection of the sensor x-axis, positive about the local vertical axis (Z) following the right-hand rule.

The data, available to the user, can be classified into two categories, the inertial data and the sensor fusion data.

FIGURE 2. Sensor coordinate frame of the Xsens Dot

1) **Inertial Data**
The inertial data comprises 3D acceleration ($\mathrm{m\,s^{-2}}$), 3D angular velocity ($^{\circ}\,\mathrm{s^{-1}}$) and 3D magnetic field (arbitrary units, normalized to 1 during magnetic field mapping), provided in the sensor-fixed frame.
The acceleration and angular velocity are derived from their respective increments produced by the SDI. Therefore, it should be noted that these measures do not directly represent the instantaneous inertial measurements, but they can be considered as a measure of the average acceleration and angular velocity in each respective time interval.

The Xsens Dot communication protocol allows the user to select *High Fidelity Mode* which integrates the inertial data on the tracker and transmits these integrated quantities to the receiver, where they are differentiated again into the inertial quantities. This process makes the data transmission more robust against package loss, hence the name High Fidelity Mode.

2) **Sensor Fusion Data**
The second class of user data consists of the 3D orientation and the 3D free acceleration of the sensor with respect to the local earth-fixed reference coordinate system (L), and are produced by XKF Core. Free acceleration ($\mathrm{m\,s^{-2}}$) is the acceleration in the local (L) frame from which the local gravity is deducted. The 3D orientations can be represented in a number of ways.

- Unit quaternions. The orientation can be represented by a normalized quaternion q = [W X Y Z], with W being the real component and X, Y, Z as the imaginary components. This format is recommended for analysis based on its mathematical advantages over the alternative representations. For visualization of 3D orientation and easy interpretation, the quaternion is typically converted into Euler angles. For convenience, the Xsens DOT SDK contains functions that facilitate the conversion of quaternions to the other representations described.
- Euler angles. Any given orientation can be obtained by three successive rotations in a particular sequence (roll, pitch, and yaw). While these Euler angles are intuitive, they can suffer from singularities. For this reason, Euler representation should only be used for interpretation, not calculation. Instead, quaternions or rotation matrices are preferred for calculations. Euler angles can also be set directly as sensor output.
- Rotation matrix. The orientation can be represented by a 3×3 matrix built from directional cosines describing the angles between the vector and the three coordinate axes.

3) Magnetic Field Mapper (MFM)

When the Xsens DOT is mounted to an object that contains ferromagnetic materials, the measured magnetic field can become distorted, causing errors in measured orientation. To correct for known magnetic disturbances, the Magnetic Field Mapper (MFM) has been developed to allow users to remap the magnetic field readings of the sensor. The MFM can be executed in a few minutes and yields a new set of calibration values that can be written to the Xsens DOT's non-volatile memory, which means it will not be erased, either by powering off or by performing firmware updates. Proper calibration of magnetic field data is crucial for the accuracy of the heading, therefore this step is of great importance. Checking if the MFM was performed correctly can be done by rotating the sensor, away from magnetic disturbances, and checking if the norm line stays stable and has a value close to 1.0. Further information related to MFM can be found in the MFM section of the Xsens DOT User Manual [15].

B. XSENS DOT SOFTWARE

1) Xsens DOT Software Development Kit and App

Xsens DOT Wearable sensor platforms also include an iOS and an Android SDK for iOS and Android mobile applications respectively. This enables developers to build their application using the SDK to scan, connect sensors, synchronize sensors, obtain real-time streaming or recording data, and benefit from many other available functionalities. A complete Xsens DOT app is also available to provide a simple way to understand the data outputs and the different functionalities of the Xsens DOT platform. The Xsens DOT app allows direct access to many of the functionalities which are also available in the SDK (e.g. scan and connect sensors, on-board data recording and exporting of the data to other devices, real-time data streaming). From the Xsens DOT app it is also possible to perform Over-The-Air (OTA) firmware updates. The communication platform supported for Xsens DOT app and SDK are Android OS 8.0 or above, iOS 9.0 or above and any other platform that supports Bluetooth 5.0.

2) Communication protocol

With wireless data transmission through Bluetooth 5.0, Xsens DOT can provide the real-time 3D orientation as well as calibrated 3D linear acceleration, angular velocity and (earth) magnetic field data to a receiving device at constant rate of 60 Hz. The Xsens DOT uses a ublox ANNA-B112 Bluetooth module, which reaches an output power EIRP of 5 dBm. The best performance is observed with Bluetooth Low Energy (BLE) 5.0, furthermore Data Length Extension (DLE) is also supported to enable faster data transfer. A lower level Xsens DOT BLE Service Specification is also provided to enable direct communication with the Xsens DOT tracker and allows one to easily build applications on other platform using Bluetooth.

3) Inter-tracker Synchronization

The Xsens DOT platform also features a synchronization process that ensures precise timing synchronization in a network of DOT sensors. Each DOT sensor has its own internal clock that runs its inertial sensors. In a network of DOT sensors, it is important to ensure that inertial sensors of all DOT units agree on a common timebase. To this end, a synchronization routine needs to be performed when using multiple sensors simultaneously. During the synchronization process, all the sensors will be time-synced to a common sensor time base. One sensor will be designated as the root node, while the remaining sensors are scanners. The root node will periodically send out its clock information in advertisement messages and the scanners will receive the messages and correct their own time domain by calculating the skew and offset of the root clock. The algorithm synchronizes the clocks to an error smaller than 20 µs, which decays to an error smaller than 1.8 ms after 30 min.

III. XSENS DOT ALGORITHMS

The signal pipeline of the Xsens DOT consists of 3 major steps that are shown schematically in figure 3. The raw data from the MEMS goes through a calibration step, that includes low-pass filtering as well, before it reaches the SDI. The third and final step is the XKF Core filter that produces the output to be transmitted over Bluetooth or stored in the internal storage.

A. STRAP-DOWN INTEGRATION (SDI)

As stated in section II, the sensor modules are inertial measurement units that contain 3D gyroscopes, 3D accelerometer and 3D magnetometers. Each module runs through an advanced signal processing pipeline that includes patented SDI algorithms data at relatively low rates [16]. These low rates range from 1 Hz to 60 Hz for Real-time streaming mode and from 1 Hz to 120 Hz for recording mode. More specifically the following output rates are available: 1 Hz, 4 Hz, 10 Hz, 12 Hz, 15 Hz, 20 Hz, 30 Hz, 60 Hz, and 120 Hz available only for the recording mode.

In traditional inertial sensing architectures, a decrease in the output frequency using linear down-sampling, results in inaccurate orientation estimates due to low sampling rates that may cause degradation in performance due to aliasing, coning and sculling effects. One of the main differences of the Xsens DOT compared to these architectures is that the pipeline of the DOT uses the SDI [16]–[18], which has the advantage of high internal sampling rates, while still providing accurate data at a lower, user-selectable output rate.

Although the low-pass filter is not specifically drawn in figure 3, the data generated by the accelerometer and gyroscope at 800 Hz is low-pass filtered with a cut-off frequency, chosen such that the low-pass region is wide enough for movement analysis applications and guarantees high fidelity in the recorded signals. The combination of the high sampling rate and the large bandwidth is essential, due to the non-commutative nature of 3D rotations [17], [18].

In contrast to linear down-sampling, the accuracy of the SDI output will not be affected by the specific choice of the output frame rate. Low frame rates will only result in reduced time resolution. In this way, highest performance is guaranteed even during very high dynamics like fast movements, vibrations, or impacts, while also reducing the communication payload.

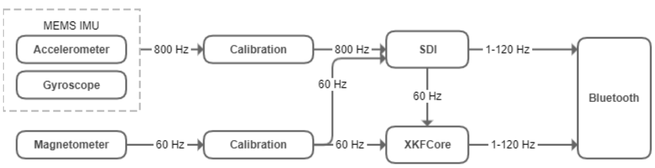

FIGURE 3. Schematic representation of the Xsens Dot signal pipeline

B. XSENS KALMAN FILTER (XKF) CORE

After the SDI has produced orientation increments, velocity increments, and magnetic field readings, the 3D orientation of the sensor is computed by Xsens' latest Kalman filter core algorithm (XKF Core) for sensor fusion, which is optimized for human motion. XKF Core uses the measurement of gravitational acceleration from the accelerometer, and Earth's magnetic north from the magnetometer, to compensate for slowly increasing errors from the integration of the rate of turn data measured from the gyroscope, while also calculating free acceleration. As described above, XKF Core makes assumptions on the range of acceleration and magnetic field sensed to obtain orientation with respect to a global reference frame. Since the reliability of the three sensors can differ between user applications, multiple filter profiles are introduced to improve the orientation estimation accuracy based on the characteristics of the movement. As a result, XKF Core is optimised to suit different types of movements and applications.

Two different filter profiles are currently available namely the general filter profile and the dynamic filter profile. The general filter profile is the default setting. It assumes moderate dynamics and a homogeneous magnetic field. When using this filter, external magnetic distortion is considered to be relatively short. On the other hand, the dynamic filter profile assumes fast and jerk-like motions that last for a short time. The dynamic filter uses the magnetometer for stabilization of the heading and assumes very short magnetic distortions. This filter can be used in applications that involve the sensor being applied on people doing high intensity sports such as sprinting. Note that the sensor fusion algorithms are primarily designed and optimised to track human motion. Devices might incorrectly interpret prolonged and intense acceleration that are far from human motion. (i.e vehicle subjected to large acceleration). It is therefore recommended to test the device for each specific use-case.

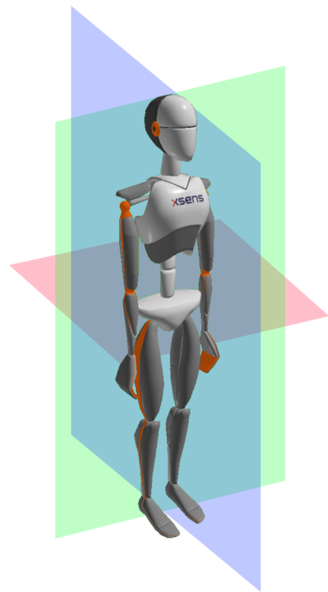

FIGURE 4. Xsens MVN avatar standing in N-pose. The three anatomical planes are shown in blue (sagittal), green (frontal), and red (transverse).

IV. MOTION TRACKING IN A MULTI SENSOR SETUP

A. BIOMECHANICAL ANALYSIS

It has become evident that it is possible to understand human motion measurement through the study of relevant data such as positions, angles, velocities, and accelerations of human body segments and joints. The data provided by a single Xsens DOT, or by a combination of multiple trackers, can therefore play a key role in the analysis and study of human motion. While a single tracker provides highly accurate inertial and sensor fusion data, the combination of multiple Xsens DOT makes use of several single sensor outputs to provide essential biomechanical parameters. The powerful algorithms described in the section above (i.e SDI and XKF-core) together with the robust inter-tracker synchronization, allow the Xsens DOT wearable sensor platform to be used in a multi-sensor set-up to provide biomechanical analysis. Thus, it is perfectly suited for solutions that aim to provide biomechanical parameters in their end product.

Joint motion plays a key role in describing human kinematics. To describe joint motion, joint angles are used which refer to the angles between the two segments on either side of a given joint. Relative segment angles can also help to depict musculoskeletal kinematics and they refer to the angles between two segments that are not connected by an explicit joint.

There are three anatomical planes to describe human kinematics, which are: the frontal (or coronal), sagittal, and transverse (or axial) planes. These planes are drawn in figure 4. Joint angles have standard names for rotations in each plane where flexion and extension refer to sagittal plane motion, adduction and abduction refer to frontal plane motion, and internal and external rotation refer to transverse plane motion. Joint angles are extracted as euler angles described by the joint coordinate systems according to ISB conventions, which is determined after a sensor-to-segment calibration procedure has taken place. Sensor-to-Segment calibration is a procedure that involves determining the axes of each segment in the Earth-reference frame when the human subject is holding a pre-defined pose.

When using Xsens DOT for human motion tracking, the sensors can be attached with straps, sleeves, physio-tape, or clips. This does not provide a rigid attachment to the actual bone, but the closest possible secure attachment that can be made externally and without invasive means. Xsens DOT incorporates Xsens patented Sensor Fusion algorithms which in turn provide high quality orientation output in the Earth-reference frame. With a specified calibration procedure conducted prior, these orientation outputs can be translated into joint angle kinematics.
These calibration algorithms and joint angle calculations are collected in the Xsens DOT Algorithm library (XDAL). XDAL is an internally used software library package that can be used in combination with the Xsens DOT and mobile SDK, and be integrated in the mobile application development.

1) Knee and Hip Joint Angles

Knee joint angles are obtained from recordings that feature at least a DOT on the lower leg and a DOT on the upper leg on the same side of the body. To achieve optimal performance the DOTs should be placed on the front side of the lower leg just below the knee, and on the outside of the upper leg halfway along the length of the upper leg. Similarly, hip joint angles are obtained from recordings that feature a DOT on the pelvis and a DOT on the side of the right or left lower leg. A DOT on the pelvis can be added, to improve the N-pose calibration, as described in section IV-A2. When all DOTs are synchronized using the synchronization algorithm described in section II-B3, the output files of the three DOTs are put into the XDAL, which calculates the knee angle based on the orientations of the two DOTs on the leg. A separate file for calibration can be used, or a user-defined period in the recording of interest.

2) N-pose Calibration

A short sensor to segment calibration phase is required before performing any acquisition in any sensor configuration. This calibration phase is required as the XDAL library gives data relative to the body segment data while the data received from the Xsens DOT SDK are sensor data. To map the sensor data to the segments, the alignment of the sensors with respect to the body segments has to be known.

To this aim, a neutral pose (referred to as N-pose) needs to be performed, in which the subject has to stand upright and straight, arms besides the body and feet directly below the pelvis, such that the feet are not touching, as demonstrated by the avatar in figure 4. While standing in this pose, calibration data is gathered such that the alignment is calculated. Two factors are important, the calibration needs to be performed in a homogeneous magnetic environment and while standing still for about five seconds.

V. MULTI SENSOR SETUP PERFORMANCE VALIDATION

To study the accuracy and usability of the Xsens DOT for sports and health related applications, an experiment was designed to investigate joint angles during gait using six healthy volunteers. The participants were equipped with both a lower body MVN Awinda system, consisting of seven trackers, as well as five Xsens DOTs. The Xsens DOTs were attached to the lower legs, upper legs, and pelvis as closely to the Awinda MTw trackers as possible. The MVN Awinda system was set up and calibrated in accordance with the MVN User Manual [19]. The accuracy of the Awinda system has been previously demonstrated [12], [20]–[23] and will therefore serve as a known reference in the present study.

The participants each performed three walking trials along a straight 8 m pathway, in which they also turned, and walked back to their starting point at their preferred walking speed. Each trial lasted approximately thirty seconds and began with maintaining a neutral pose for five seconds, which is used by XDAL to perform sensor-to-segment calibration. The MVN Awinda data was collected at 100 Hz, while the DOT data was collected at 60 Hz using the on-sensor recording option. The MVN Awinda data was reprocessed in MVN Analyze Pro 2021.0, which yields the flexion/extension (FE) angles of the hips and knees. FE angles were also obtained from XDAL for the DOT data. It is important to note that, even though the subjects were wearing five DOT sensors, a pair of two DOT sensors placed on adjacent segments is enough to obtain a joint angle. The set-up of five DOT sensors enables

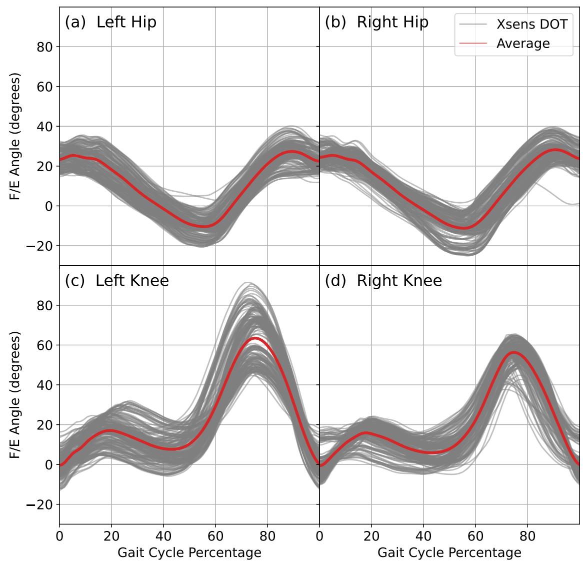

FIGURE 5. All gait cycles measured by dot (gray) and their averages (red). The Flexion/Extension angles are shown for (a) the left hip, (b) the right hip, (c) the left knee, and (d) the right knee

Joint FE	RMSE (°)	Pearson coefficient
Left Hip	2.77	0.992
Right Hip	3.03	0.989
Left Knee	6.66	0.974
Right Knee	5.66	0.979
Overall	4.53	0.983

TABLE 1. RMSE and Pearson coefficient values of the difference between DOT and MVN Awinda per joint averaged over all gait cycles.

the recording of both knees and both hips.

To facilitate a proper comparison between the calculated joint angles, each set of data was aligned in time and a fixed offset was subtracted from both curves such that they both start from 0 degrees. The FE angles captured by DOT and MVN Awinda were time-normalised to the length of each gait cycle starting at a heel strike. The heel strike moment was defined as maximum knee extension after maximum hip flexion. All individual gait cycles are shown in gray in figure 5 while the average gait cycle of all participants and trials is shown in red. The RMS value and Pearson coefficient, R, of the difference between the DOT and MVN, averaged over all trials, are presented in table 1. It should be noted that these values do not describe differences between subjects, since the difference is not calculated between an individual gait cycle and the average gait cycle, but rather between the DOT and MVN Awinda recording of the same gait cycle.

The error metrics in Table 1 show that the DOT tracking

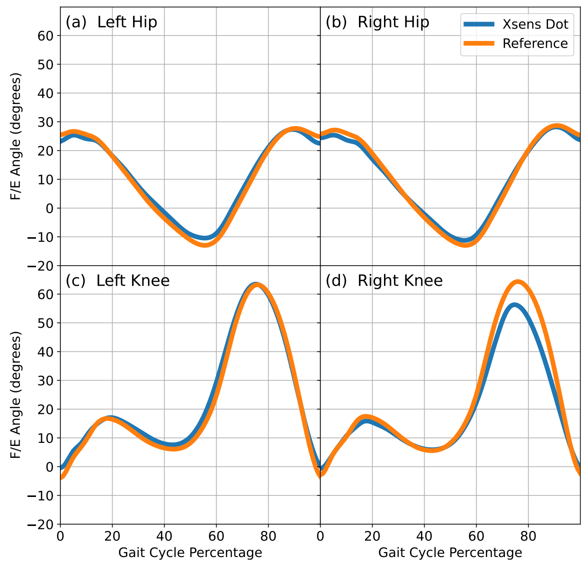

FIGURE 6. Averaged Flexion/Extension gait cycles of DOT (blue) and MVN Awinda (orange) are shown for (a) the left hip, (b) the right hip, (c) the left knee, and (d) the right knee

of the knee FE is slightly less accurate than it is for the hip. This can primarily be attributed to the sensor-to-segment calibration. Where MVN Awinda employs an additional dynamic calibration routine, DOT + XDAL may suffer some errors from the more basic static calibration. The pelvis sensor is important in determining the frontal plane, which can lead to larger calibration errors further away from the pelvis, as is observed in this experiment. Part of the joint rotation is then attributed to the wrong plane of motion. The left knee has the highest RMSE, which is caused by larger variation between the subjects, as can be seen in figure 5(c).

Overall, this experiment demonstrates the usefulness and effectiveness of Xsens DOT + XDAL in gait experiments. With minimal up-front set-up and calibration efforts appropriate joint angle estimates can be obtained. This comes with the additional flexibility of leaving out sensors that are not required for the user's experiment. The user could limit themselves to the left leg, which reduces the number of sensors for DOT.

VI. CONCLUSION

In this white paper, the basic working principles and architectural design of the Xsens DOT system have been presented and motivated. The high sampling rate of the inertial data, together with the use of the SDI, preserves accuracy even at lower update rates or occasional packet loss. The BLE protocol ensures universal connectivity with mobile devices. The usefulness of the DOT platform and the algorithm library is demonstrated in a basic biomechanics experiment. The RMS error between DOT and MVN Awinda for gait is $4.53°$ and the Pearson coefficient was found to be 0.983. From these metrics it can be concluded that the Xsens DOT can be used as a flexible, easy and reliable tool for capturing human motion in a variety of applications.

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