Inertial Measurement Units in Gait Analysis Applications
Questions, Suggestions and Answers

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Abstract: The paper deals with inertial measurement units (IMU) and their application in gait analysis in the wide range from movement monitoring through rehabilitation feedback to sports improvement. An IMU sensor incorporates three microelectromechanical sensors - triple-axis gyroscope, accelerometer, magnetometer – and, optionally, a barometer. The outputs of all sensors are processed by an on-board microprocessor and sent over a serial interface using wired or wireless communication channels. The on-board processing may include sensor conditioning, compensations, strap-down integration as well as determination of orientation. The sensor output is sent to applications working on standard PC, tablets or smart phones using different sampling rates. The output data of one IMU sensor allow motion analysis of the sensor unit itself as well as the motion of the limb where the sensor is mounted to. Using a combination of two or more sensors the movement of limbs/legs can be compared; their relative motion can be investigated; angles can be calculated.

In general, in motion and gait analysis, we like to get primary information about the position of all interesting points, the orientation of the limbs and the joint angles at each moment of time as well as derived averaged and summarized characteristics about the motion and the gait. Based on our own investigations the paper discusses how much information is really necessary to determine gait events and gait features for different purposes.

1 INTRODUCTION

Inertial measurement units (IMU) are freely available at the market: from low cost boards or sticks to relatively expensive sensors assembled in small and light weight packages. An IMU sensor incorporates three microelectromechanical sensors - triple-axis gyroscope, accelerometer, magnetometer – and, optionally, a barometer. The outputs of all sensors are processed by an on-board microprocessor and sent over a serial interface using wired or wireless communication channels. The on-board processing includes sensor conditioning, compensations, strap down integration (SDI) as well as determination of orientation. Otherwise post-processing tools are provided to perform these calculations, e.g. to calculate orientation. 9 DOF-IMU sensors including data acquisition software and software development kits (SDK) are provided, e.g., by Shimmer (www.shimmersensing.com), Xsens Technologies (www.xsens.de), stt engineering and systems (www.sst-systems.com), life performance research (www.lp-research.com), Kionix (www. kionix.com), Noraxon (www.noraxon.com), Analog Devices (www.analog.com). IMU sensors are applied for motion capture, measurement, processing, navigation and control. In this paper we consider only applications related to the gait analysis and healthcare. Many companies providing IMU sensors developed software products for research, clinical needs, rehabilitation and sports (Xsens MVN Biomech, sst clima, noraxon clinical). Small companies develope purpose oriented, low cost tools like RehaWatch (www.hasomed.de). Based on the data of a number of IMU sensors (17 in MVN Biomech) and the kinematic model of the human body various derived values and features are determined:

- position of characteristic points, orientation of limbs, angles of joints at each moment,
- cadence, distance and velocity of motion, index of symmetry,
- characteristics of each or averaged stride like initial and terminal point, length, height,

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circumduction, relationship between stance and swing.

IMU based motion capture systems are usually compared to the accuracy standard of conventional optical motion capture systems such as Vicon (www.vicon.com). Sometimes they are considered to have the same accuracy. Alternatively the output of IMU based calculations can be proofed using high accurate position measurement systems like API Radian (www.apisensor.com) or comparing with well-known results from gait observations and analysis (Perry, 2010, Murray, 1964).

Since we have been working for a long period on this topic, mostly in student projects, the aim of this position paper is to ask questions and to try to give answers.

2 SYSTEMS AND EXPERIMENTS

Since about five years we have been using sensor systems for the acquisition of various bio-signals like ECG, EEG, EMG or motion data. Sensors applied directly to limbs/body were tested as well as position measurement systems which in-motion data acquisition and are used for comparison. A-priori knowledge about gait patterns and kinematic models of the human skeleton are involved in algorithms as well as in plausibility tests.

In the field of motion analysis we have been focused on human gait with respect to health applications e.g. in orthopaedics, physiotherapies and rehabilitation. The motion of the patient is relatively slow (~1-2 m/s) with moderate changes of the linear and angular velocity.

In clinical practice experts observe the movement of patients going straight forward about five to ten strides. Assistant measurement systems and applications will be able to quantify those observations, to make them comparable and traceable over time. In this paper we discuss the last experimental setup where 9DOF Xsens sensors were placed on the pelvis and all lower limbs, forming together the kinematic gait chain.

2.1 Systems

2.1.1 IMU Sensors

In the current experiments we use up to seven 9DOF Xsens MTw sensor units connected via Bluetooth to one Awinda station and data acquisition software "MT Manager". On-board the data of the primary sensors are sampled with 1800 Hz, strapped down by integration (SDI) incorporating the estimate of orientation to the transfer rate of 100 Hz for two or 60 Hz for seven MTw. Finally the "MT Manager" provides synchronized data from all involved MTw (< 10 µs accuracy), i.e., linear acceleration a, angular velocity ω, magnetic field m and quaternion q (orientation estimated on-board < 1° of static and 2° RMS of dynamic accuracy (www.xsens.de).

Before starting measurements sensors need calm or slow motion to "warm up the filters", to calculate the initial orientation of the sensor with respect to the world coordinate system. The implemented Xsens-Kalman-Filter is based on the assumptions that on the average the acceleration due to the movement is zero and that the magnetic field is homogenous or steady state.

2.1.2 Gait Pattern

In the middle of the last century Perry (Perry, 2010) and Murray (Murray, 1964) observed, measured and analysed the normal human gait. The gait pattern covers one stride, the full period of movement of one leg, one stance and one swing phase. The given pattern includes average trajectories of joint angles (hip, knee and ankle), the angle between thigh and vertical (in sagittal plane) as well as average trajectories of the center of hip (pelvis). They discovered several gait events, e.g. initial and terminal foot contact to the floor, heel strike, flat foot, heel off, toe off. Events disjoin the stride into stance and swing phase as well as into eight more detailed sub-phases.

2.1.3 Kinematic Model

On the base of a planar model of the kinematic chain of lower limbs average trajectories of hip, knee, ankle, middle foot and toes are derived from a given gait pattern (position, linear and angular velocity and acceleration). These patterns allow the identification of correspondences between gait events and characteristic points of acquired or derived data (minima, maxima, zero crossings).

2.1.4 Position Measurement

The API Radian laser tracker was used to measure the movement of the foot and the ankle with 1 kHz sampling rate and accuracy of 50 µm. To process the measurement a relatively heavy controller ball is to be mounted to foot or ankle. The ball dynamics may not be neglected (impact of heel strike in vertical direction).

2.1.5 Motion Capture

Canon EOS 5D was used to record the movement with 60 fps - the sampling rate of each Xsens Mtw sensors (for seven IMU). Two strides were captured with a resolution of 1280 x 720 px, so that it is possible to reference gait events to single frames.

2.1.6 Evaluation Software

To answer various questions and to evaluate several approaches we have developed an open MATLAB script which is organized to process experimental data automatically step by step. After each step the intermediate results are saved. Optionally, figures can be created and written to hard disc. In dependence of the task steps can be skipped or repeated. The following steps are included:

- reading and reorganizing sensor by sensor the acquired data, given in the sensor related coordinate system (SCS),
- estimation of orientation (quaternion), if necessary, using the Madgwick algorithm (Madgwick, 2011),
- transformation of sensor data into world coordinate system (WCS),
- calculation of orientation relative to the initial one,
- calculation of angles between z-axes of a sensor and the vertical or the horizontal plane,
- calculation of various features as candidates for gait events,
- detection of inner strides,
- determination of direction of movement, transformation of the sensor data into motion coordinate system (MCS),
- integration of acceleration to calculate velocity and position data stride by stride,
- calculation of stride related and average features,
- determination of average stride,
- calculation of joint angles, if relationship between the sensors is given,
- calculation of symmetry ratios, if couples of sensors (left and right) are given,
- extraction of gait characteristics.

2.2 Experiments

The described experiments were designed this summer, first, to acquire input data for the evaluation software and, second, to prepare a “standard” experiment addressed to a large number of healthy subjects for statistical analysis. To have the chance to attract later on experts the movement was partly recorded (> 2 strides per leg).

2.2.1 Experimental Setup

Xsens MTw sensors are attached laterally pairwise on left and right lower limbs at shoes below knees, at thighs, and one on back (pelvis) as shown in figure 1. The camera was placed about 15 cm above the floor, 5 m from and orthogonal to sagittal plane of the subject.

Figure 1: Alignment of the sensors.

2.2.2 Evaluation

The movement of two healthy subjects, one female and one male, mid-twenties, was observed. They were asked to choose the speed for normal, slow and fast walking themselves passing a distance of about 10 m twice from left to right and back. After some time the same experiment was repeated. The experiments were executed indoors where magnetic field was neither homogenous nor steady state as learned during the post-processing of data.

3 DISCUSSION AND RESULTS

This contribution is a position paper allowing to outline questions followed by our suggestions and current answers. Both can be treated as a source of discussions.

Most of the results stated in the discussion belong to sensors mounted on left or right shoe (foot) acquired with 60 Hz; otherwise it will be mentioned.

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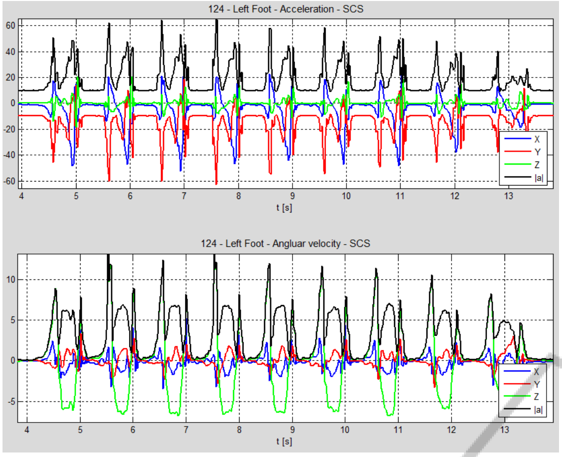

Figure 2: Acquired acceleration and angular velocity with respect to SCS (black – length of the vector).

Do the acquired data figure out the periodicity of movement stride by stride?
Repeating patterns obviously appear periodically, varying little from stride to stride (see figure 1). During stance phase acceleration is close to zero, during swing phase large changes are typical.

Can the number of strides simply be counted?
Repeating patterns are clearly separated. Each pattern can be assigned to one stride, so that the number of patterns is equal to the number of strides. The first and last step is incomplete (see last pattern in figure 2). Both feet are side by side before and after movement.

Is acceleration due to movement dominant in relation to g? Is its average zero?
Yes, peaks of acceleration are up to 6 g. Walking is characterized by change of stance and swing phases, so that average of acceleration is zero periodically after every second.

Is there any predominance of components of acceleration or angular velocity?
Forward component of acceleration (direction of movement) dominates vertical one. Lateral component of angular velocity is dominant.

Does it seem to be possible to determine, e.g., length of stride or passed distance, from sensor data without transformation into WCS?
There are several software systems like RehaWatch and papers (e.g., Orlowski, 2013) showing that it seems to be possible. Sensors need to be mounted with high accuracy such that SCS coincides with WCS at calm (stance phase). Small and short rotations of sensors are neglected.

What can the quaternion of orientation be used for?
The orientation is not measured, but estimated from angular velocity, acceleration and magnetic field. If orientation is related to WCS components of all vectors are transformed into that inertial coordinate system. Gravitation vector g can be eliminated. Various angles, e.g., between sensors, vertical and floor as well as changes of angles between sensors, can be easily calculated.

Are the algorithms of Xsens and Madgwick comparable?
The Xsens-Kalman-Filter (Roetenberg, 2009) is implemented on-board the Xsens MTw sensors. The algorithm of Madgwick is implemented in post-processing of acquired sensor data. Because of heterogeneity of magnetic field orientation was estimated only from angular velocity and acceleration. Gait features were calculated using the same algorithm. Differences of about 5% are noticeable, e.g., average length of stride is mostly larger for the Madgwick algorithm.

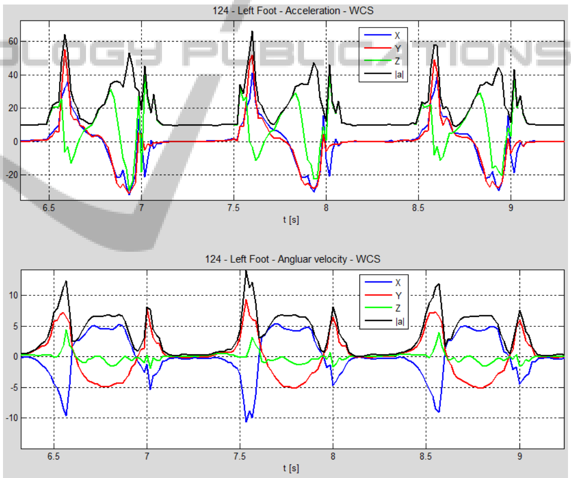

Figure 3: Acceleration and angular velocity with respect to WCS (black – length of the vector).

Which definition of gait cycles is goal-oriented with respect to the integration of the acceleration?
There are various possibilities to determine the gait cycle (GC). Movement starts and finishes at calm. Any significant moment of the stance phase, where the velocity of foot is zero, can be used as transition point from one stride to the next one. In principle any other significant moment, e.g., maximum of angular velocity vector can be considered as the transition point too. Perry (Perry, 2010) proposed the initial contact point (IC) as the beginning of GC. Stride-by-stride integration should start at a moment of calm (velocity equal zero) or at least at minimum of motion.

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Are there any features of data indicating transition from stride to stride?
To find indicators of the transition point all measured and derived data can be considered. Manifold ideas are given in literature (e.g. Green, 2010) focussing on points nearby IC, maximum of lateral component of angular velocity, forward component of acceleration or angle between foot and ground. In our algorithm the minimum of weighted sum of acceleration and angular velocity (maximal calm) is used. This indicator is significant for whole stance phase, so that additional plausibility checks should be added.
How can the direction of movement be determined in WCS?
While z-axis of WCS coincides with vertical the other axis are in horizontal plane. Integrating horizontal components of acceleration velocity vector is calculated. It defines the current direction of movement. WCS is rotated about vertical so that x-axis of resulting MCS coincides with direction of movement.

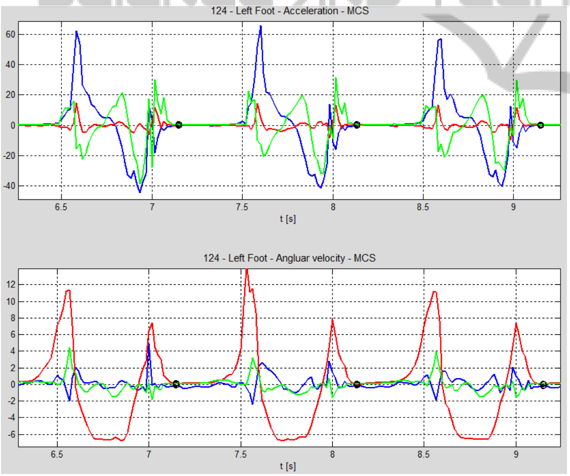

Figure 4: Acceleration and angular velocity with respect to MCS (black–begin of integration).

Does measured stride coincide with normalized gait pattern?
Comparing figures 4 and 5 the similarity between gait pattern given by Perry (Perry, 2010) and our data is obvious.
Is the integration stride-by-stride preferable in relation to integration over the whole movement?
Choosing integration intervals, so that acceleration average as well as initial and end velocity are equal to zero, algorithms work very well (foot sensors). In our algorithms we considered only inner strides, excluding first and last half-strides (figures 6 and 7).

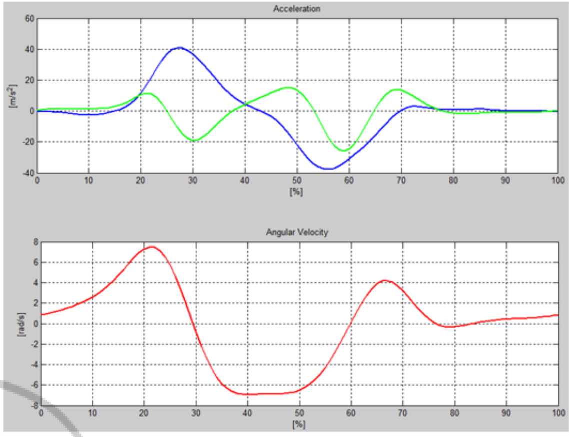

Figure 5: Pattern of acceleration and angular velocity (Perry, 2010).

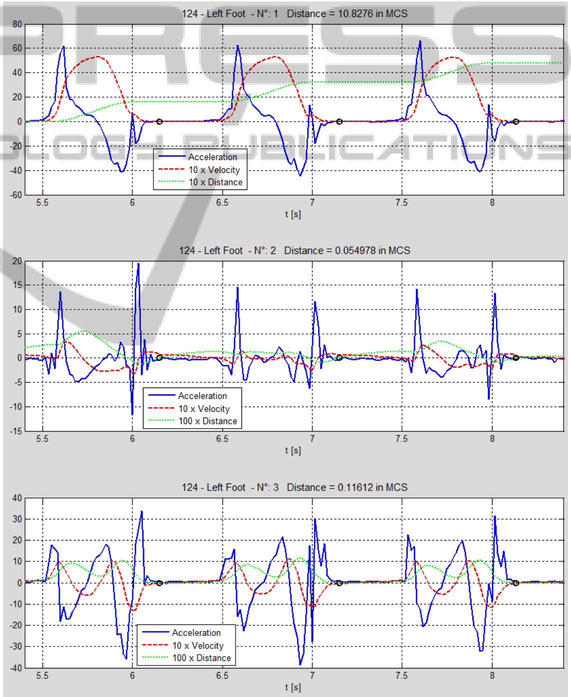

Figure 6: Measured acceleration, calculated velocity and displacements – forward, lateral and vertical.

Are the algorithms applicable considering the movement to other sensors?
The assumption, that initial and end velocity equals to zero, is not fulfilled for sensors mounted above the ankle. Their unknown minimum velocity (during inner strides) increases with the distance from ankle. The detection of transition points should be improved because of absence of calm.
Is there any chance to estimate the minimum velocity for other sensor locations?
Unknown minimum velocity can be estimated, first,

based on of a model or, second, through including first and last stride into the integration interval. During those strides acceleration average is not zero.

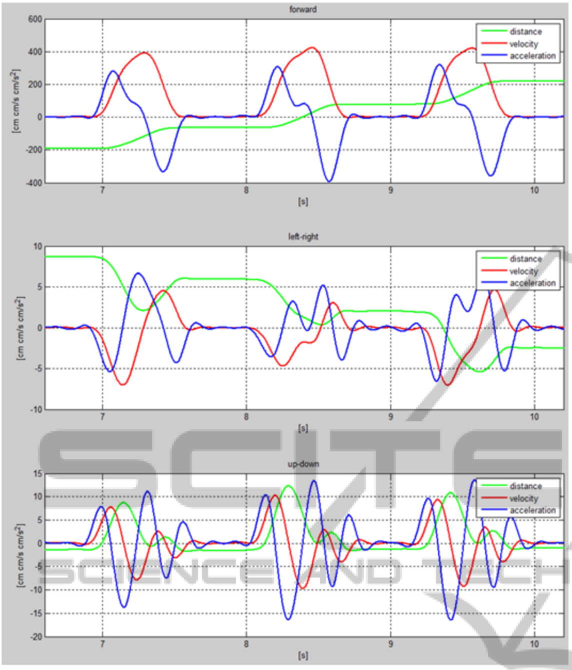

Figure 7: Measured displacement, calculated acceleration, and velocity– forward, lateral and vertical – using API Radian.

Which and how many GC have to be involved in the calculation of average and standard deviation?

First and last strides are used to accelerate (decelerate) before establishing steady movement. To determine average only inner strides, not less than 5, should be considered. The exact selection of all GC and scaling to 100 % seems to be very important.

Is there any advantage to include two or more sensors into algorithms?

Including two or more sensors into algorithms offers a lot of chances: to calculate angles between two sensors (joint angles), to compare their behaviour (symmetry) or to include improvements based on kinematic relationships.

Does model-based calculation promise large improvement of accuracy?

The Xsens MVN Biomech studio is based on 17 sensors and biomechanical skeleton model. It is used in motion capture as a substitute of optical systems. Following model-based algorithms promise improvement of accuracy even in small systems.

4 CONCLUSIONS

The evaluation algorithms work well regarding the data of foot sensor. Sometimes there are problems with the accuracy of transition points between swing and stance, i.e. starting points of the stride-by-stride integration. Improvement of their accuracy can be achieved including more features as well as more sensors. At the same time calculation of average stride will be improved and, following, the symmetry analysis based on average GC. Algorithms incorporating only one sensor and processing integration stride by stride maybe applied to other sensor location. If the absolute velocity should be determined, the question of the steady part of velocity has to be solved. Steady part increases with the distance of sensors from floor. Model-based calculation may be goal-oriented in this context, as well as for the determination of joint angles and symmetry indexes.

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