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TESI DI LAUREA TRIENNALE IN INGEGNERIA BIOMEDICA

EXPERIMENTAL VALIDATION OF XSENS INERTIAL SENSORS DURING CLINICAL AND SPORT MOTION CAPTURE APPLICATIONS

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Ai miei cari,

per il continuo e sentito sostegno.

Ad Anita,

senza lei, queste pagine

non sarebbero state scritte.

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PREFACE

Motion analysis aims to objectively measure body segments movement (kinematics), ground reaction forces and joint motion (kinetics) as well as muscles activity (electromiograpy). This discipline has primarly two areas of application: clinical and sport. In the first one motion analysis can be employed for example in the diagnosis of gait kinematics and kinetics alterations, in the monitoring of the rehabilitation after injuries or surgeries course but also for prosthesis and orthoses evaluation. Sport applications are referred to the functional evaluation of specific aspects of the performance as well as to optimize the training process.

Motion analysis can be performed with several instrumentations which differ for invasiveness, accuracy and costs. Furthermore, considering the technology of these systems, 4 categories can also be defined: optical, mechanical, magnetic and hybrid. Nowadays stereophotogrammetric system is the most employed in biomechanical laboratories: it is considered the golden standard for its accuracy even if it presents some limitations regarding the subject preparation, the indoor employment and the operating volume due to the number of cameras.

The interest on Inertial hybrid sensors is growing both considering entertainment applications but also biomechanical ones as for example ergonomic and sport measurements. The main advantage of such instruments is the outdoor employment with no limit of operating volume. In this way it is possible to record real movements in ordinary environment.

Therefore the first aim of the present work was to evaluate the accuracy of the inertial system MTw developed by Xsens Technologies in clinical and sport applications. The followed approach was to compare technical frames of both MTws and optoelectronical system . The second aim was to define the anatomical rotation axes to obtain the most important data in clinical application: the anatomical angles calculated by joint coordinates system.

CHAPTER 1

Introduction

1.1 Motion Capture

Motion Capture is a discipline that studies the human body movement, in order to have an objective and accurate measurement of :

- body segments movements (kinematics)
- ground reaction forces and joint moments (kinetics)
- electrical muscle activation signal (ElectroMyoGraphy)

Motion Capture is defined as the procedure of recording movements of objects or persons, therefore it has several area of application, that will be listed in what follows:

I. Clinical applications: in the prosthetic field, both structural design and characterisation; for movement control and rehabilitation; as well as analysis of balance system, to control and have a deeper knowledge of pathophysiology of the skeletal and locomotor apparatus.

II. Sports applications: to increase athletes performance preventing injuries with a qualitative analysis identifying harmful movements that have to avoided during training.

III. Ergonomic applications: analysis of human body movements can give the possibility to create devices with more comfortable and useful design, right to biomechanical rules.

IV. Entertainment applications: to create animated films or video games with more natural movements and actions.

V. Other applications: virtual reality, robotic etc.

Motion tracking started as a photogrammetric analysis, conducted by Eadweard Muybridge in 1870 – 1880, who proved that a horse can have all four hooves lifted off the ground while galloping. Later Muybridge also conducted a human movements studies. Etienne-Jules Marey has been the first person to analyze human and animal motion with video in the end of XIX sec, he also invented a “chronophotographic gun ” which could take 12 consecutive frames per second.

Fig 1: Marley’s photographic gun

In 1931 Harold E. Edgerton invented ultra-high-speed and stop-action photography, called stroboscopic photography. This technology can record images at high speed and results are more similar to a video rather than a photo, it's natural with this devices to obtain more details than a single picture and, indeed the cinematography quickly became the principal MoCap system, although it had a very low accuracy and slow data elaboration. The turning point was the introduction of digital technology which it lets an automatic and very fast data elaboration by using calculator, moreover, thanks to this new technology, new MoCap system had been created; nowadays, the best of these systems can measurement the movements in real time, with an accuracy less than 0.5 mm.

A Motion Capture system can be assembled in different way, using various technology; it's so possible to define four approaches to realize a MoCap system:

- Optical systems
- Mechanic systems
- Inertial systems
- Hybrid systems

MoCap system created by one of this approaches, has characteristics linked on the technology used, that should be valued case to case.

At this moment, the optical system, called optoelectronic system, is the most accurate and used MoCap system for analysis of movement.

1.1.1 *Optical Systems*

Optical systems are based on photography or video-recording, using different technologies approaches and methods. The most simple and fast optical system for MoCap is the 2D cinematography system: consist in a video-recording with a camera and a computer processing. The second step allows:

- link frames with background matching
- define the size of a known object on the movement plane
- draw remarkable points' track
- calculate absolute and relative angles between body segments
- calculate angular or linear velocity

Fig 2: Long Jump © Dartfish

The next step is cinematography the 3D system, that consist of a collection of video data from multiple commercial cameras, which enables, after data interpolation by a software processing, to obtain 3D data of markers. This technique has the same approach as the optoelectronic system, but it is performed by commercial cameras, involving less accuracy and less sample rate than optoelectronic system. The main advantage is the possibility to perform analysis directly on the competition field.

A new 3D video motion capture system is formed only by a video data, without markers or sensors. The human body is recognized by a special computers algorithms that analyze multiple real time video data. This method is often used by a entertainment applications, first of all in video games area; for example the commercial Microsoft device Kinect can recognize gamers body (with a RGB camera and IR-camera for defined the depth) and this allows to have a “gamers controller”. This method is used to move animated characters: the human body movements processed by a software, are the input arguments of a graphical animated software; in this way the virtual figures will do the same movements of the human characters.

The most used and accurate system at today for MoCap, is the optoelectronic system; it's compound by infra red cameras, infra red strobes, active or passive markers, three axes frame with markers for calibration and model defined by operator.

Optoelectronic system needs six or more cameras to perform analysis (the number can change due to study and accuracy level required) because for calculate 3D position of markers every single marker must be recorded by two or more cameras. Every camera can identify the direction between optical camera's centre and where markers reflects the infra red on the sensor. Knowing the direction it can obtain the straight line through this two points and, the intersection of two straight derived by two cameras, allows to identify the 3D marker position. The markers are small spheres and it can be active or passive: active markers generates different colours' light, in this way the cameras can identify single marker, however this type of markers needs power supply; the second one are covered by a refractive material, that reflect infra-red produced by strobes, nevertheless in this case for identify single markers it's necessary to have static markers position and define a "position model". Performing an optoelectronic recording, needs specific setup steps: first in all the cameras must be placed around the volume of calibration, in hexagonal way (if there are 6 cameras), trying to avoid alignment of cameras. During this phase the system detects the global system of reference, physically determined by a three axes frame with markers, placed in the centre of the volume of calibration. After the calibration, for every camera the orientation is calculated, as well as the position, the focal length, the optical centre position and the distortion parameters. All of this information are necessary to perform 3D reconstruction. The calibration must be done for a volume proportional with the act to study, because if the volume is too large, the accuracy will be minor, however if the volume is too small, the act couldn't be recorded in total.

Passive markers must be placed on the subject following the position model defined, so it's possible to identify every single marker by its position. This is fundamental for data reconstruction step. In the analysis data step, every body segment with markers is represented by a rigid body (is assumption like the segment's bone), from which is possible to obtain physiological and anatomical movements. It's very important to minimize every other movement of markers, due to muscle and skin effect, because only if this hypothesis is verified, it is possible approximate a body segment like a rigid body. In the human body there are some points really near at bones processes, where there aren't muscle bundles which can be activated during movements, this points are calls "Anatomical landmarks". These are the preferred locations of markers to verified the hypothesis before exposed.

To identify a body segment a group of markers (usually 2 or 3 markers) is needed and it allows to define the reference system linked to that body segment, with which it's possible to obtain the reconstruction of the movements of the body with respect to the laboratory reference system (set by calibration step) or with respect to another body segment.

Fig 3: Example of markers application

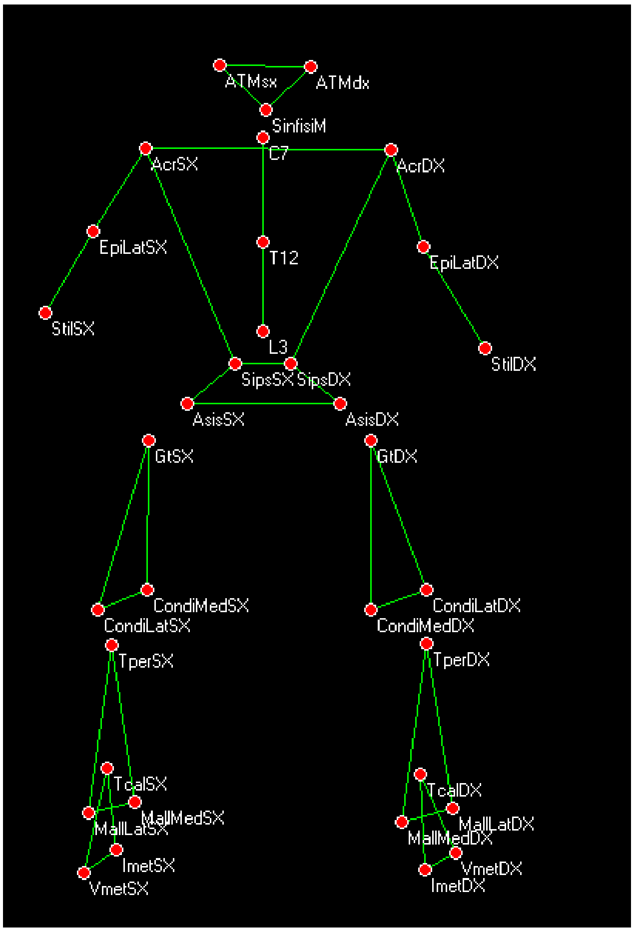


Fig 4: Example of optoelectronic model

1.1.2 *Mechanic Systems*

One of the first systems used for human movements analysis was electrogoniometers, which are a device is able to measure angle between two segments. Before wireless connection, the biggest defect of this devices was wires interfered with subject movements, however at today the principal limits of this product are low accuracy and encumbrance on the subject's body. The electronic evolution, in particular with Micro Electro Mechanical Systems (MEMS), allowed to create new and smaller sensors, some of which find application for create MoCap sensors. The most important sensors for analysis of movements sector are accelerometers and gyroscopes:

- Accelerometer is an electromechanical device that measures acceleration force, both static and dynamic. A basic accelerometer consisted of two fundamental parts: a case that will be attacked to the object whose necessary measuring acceleration, and a seismic mass suspended by a spring, fixed on the case. When object is accelerated, due to this motion, the spring contract and shorten itself following seismic mass movements which are proportional to acceleration; knowing the inertia and the displacement position of mass, it is possible calculate the acceleration (this job is done by a different sensor that differences the kind of accelerometer: strain gauges, piezoresistive, piezoelectrical, laser, capacitive..). If 3 accelerometers are arranged like a X-Y-Z frame, it becomes a 3-dimensional sensor which can measure accelerations in every space directions. MEMS accelerometers are created using Silicon and, between all, the ones which use capacitive effects have excellent characteristics. Difference of capacitor can be caused by a variation of one of this three parameters:

$$C_0 = \varepsilon_0 \varepsilon_m \frac{A}{d}$$

ε_m is the permittivity of the material between two armors, A is the area of them and d the distance between them. Typical MEMS accelerometers is composed of seismic mass with plates attached with springs to fixed plates by a mechanical suspension. This two plates formed the capacitors. Every movements of proof mass causes a change in capacity which is proportional to the acceleration.

Known mathematical and physics knowledge allows to obtain velocity and position starting by acceleration.

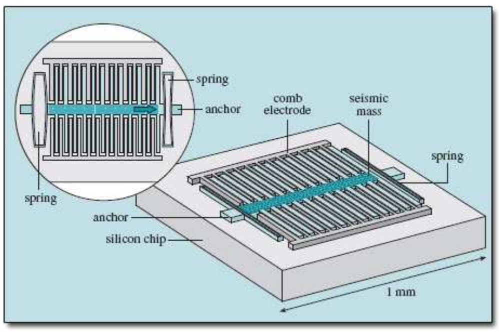


Fig 5: Detail of a typical MEMS accelerometer

Fig 6: ADXL 320 accelerometer

- Gyroscopes are a devices which can measure or maintain the orientation using the law of maintenance of angular moment (angular moment of a system is constant if the result of eternal forces applied to the system is null). This devices tends to maintain its axle oriented in a fixed direction, regardless of rotations of its frame. A basic conceptual gyroscope can be made with a rotor (disk or wheel) insert in a gyroscope frame, when the rotor is rotating, its spin tend to maintain it parallel to itself, doesn't let change its orientation.

As accelerometer, gyroscopes is product with MEMS technology in different type: vibrating ring gyroscope, macro laser ring gyroscope, piezoelectric plate ring gyroscope, fiber optic gyroscope and, at last, tuning fork gyroscope which is one of the most widely use gyroscope. All MEMS gyroscope take advantage of the Coriolis effect: a moving mass M with v velocity, rotating in a reference frame at angular velocity ω affected by a force:

$$F = 2Mv \times \omega$$

Tuning fork gyroscope is composed by two masses that are built in such a way as to oscillate with the same intensity but in opposite directions. When rotated, is generated a Coriolis force that it is bigger when mass is further away from the spin, this creates an orthogonal vibration that can be detected by different methods.

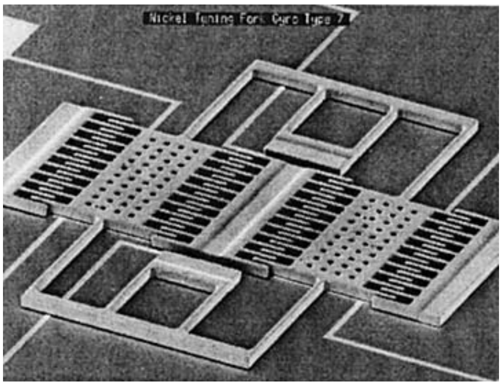


Fig 7: The first working prototype of the Draper Lab gyroscope

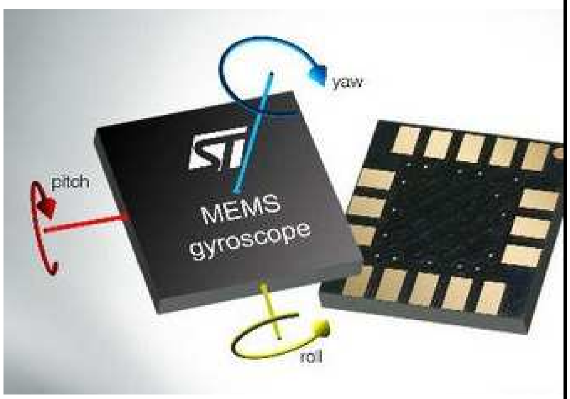


Fig 8: Example of a modern gyroscope

Usually, this two devices are used together because accelerometer's accuracy is limited; unfortunately, the accuracy of these sensors is still lower than standard for MoCap systems.

Another mechanical device invented for MoCap area which implements new technologies, are optical fiber system: this technology allows to create flexibility sensors for evaluate bending angles. Optical fiber sensors allows freedom of movements, thanks to flexibility of fiber, it can place on a human subject obtaining in output 3D movements of a human skeleton. These devices are versatile and easy to use, however, also in this case, the major limitation consists of a low accuracy; anyhow optical fiber are usually used for didactical and entertainment applications.

1.1.3 Magnetic Systems

Magnetic sensors represent other important devices employed in the MoCap field.

They exploit the property of magnetic field to identify position of sensors and its movements, this system is composed by a low-frequency transmitter source and sensors which must be placed on subject's body segments. The transmitter generate three perpendicular (one to each other) magnetic fields for every measurement cycle and this is possible because the transmitter are formed by three perpendicular coils crossed in sequence by the current. Each 3D magnetic sensor can measure strength of those fields which is proportional to the distance between sensor and source, besides both sensors and transmitter calculates positions of each sensor from the nine output data of magnetic field strength per sensor. This devices have two main problems: magnetic fields decrease in power rapidly, for this reason there is a maximum distance between sensors and transmitter; also the second problem is linked to magnetic field property, in fact it is very sensible to ferromagnetic materials which can create disturbances, decreasing the accuracy of the measurement. Magnetic sensors have a peculiarity: they don't suffer from "problems of visibility", human body in fact is crossed by magnetic fields used and this allows to have not dark points during movements. Another important characteristic is the constant accuracy of this devices, they can calculate position and orientation with the same accuracy (if the magnetic field power sensing by the sensors is constant).

1.1.4 Hybrid Systems

Hybrid systems are new MoCap approach, these devices implements more than one MoCap systems previously exposed, they trying to integrate advantages of systems of which they are composed and, at the same time, decrease, or, if it is not possible, don't increase, the systems' limits. There are several types of hybrid systems, all of them with different characteristics. An example is hybrid system formed by inertial and magnetic systems, which can be measure three dimensional position and orientation of all body segments in real time, linking inertial and magnetic systems property.

1.2 Terminology and conventions

"Anatomical position" is the universal starting position for describing movements and, in this position, three motion planes can be defined:

- Median/Saggital plane
- Frontal/Coronal plane
- Horizontal/Transverse plane

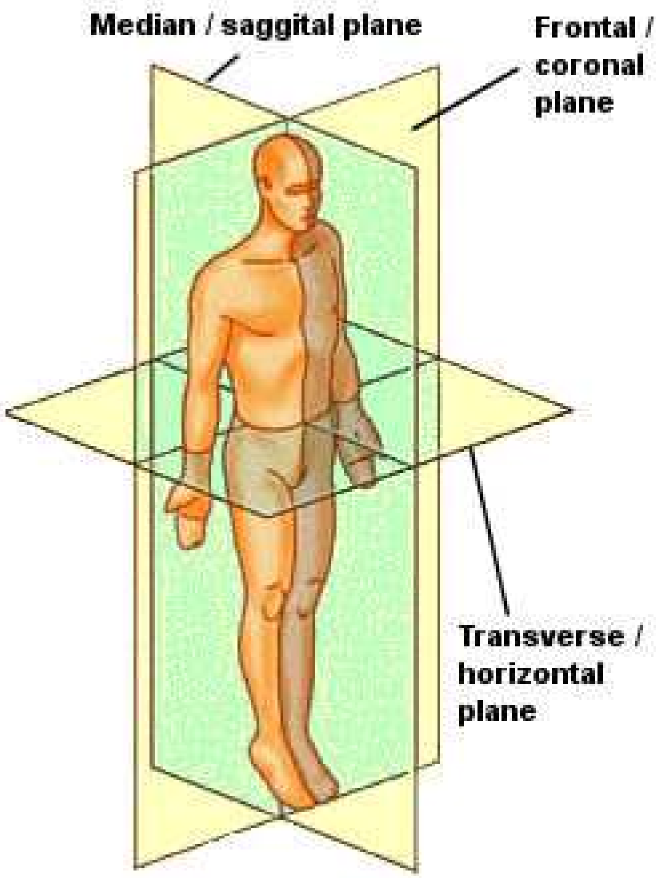


Fig 9: anatomical position

To define respective position about structure, there are exactly terms: proximal, meaning nearer, and distal, which means more distance, both respect to origin of anatomical of interest part (for the arts is the attack on the body); for example, greater trocanther is proximal and medial/lateral epicondyle is distal.

Like position, also movements must be described with a specific terminology:

- Flexion is the movement that decrease angle between share joint
- Extension is the movement which increase angle between share joint
- Adduction means approaching a movable body parts (such as the leg) to the median plane
- Abduction is the opposite movement of adduction
- Intra rotation is a movement from lateral to medial
- Extra rotation is the opposite motion of intra rotation

CHAPTER 2

References

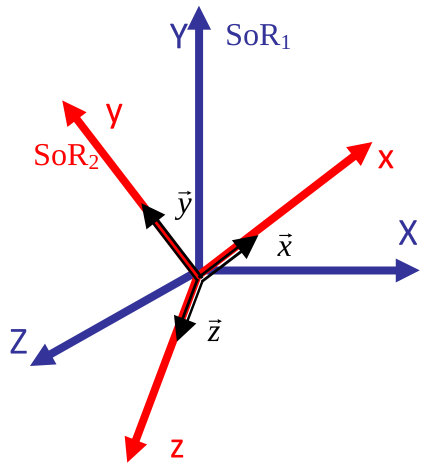
2.1 *Rotation and Orientation Matrix*

Rotation and orientation matrix are basic algebraic means used to perform rotations in Euclidean space. A rigid body ***B*** is a collection of point in the three dimensional space, bounded by following relation

$$\left\| P_i(t) - P_j(t) \right\| = \cos t \qquad \forall i, j \in B$$

which imposes that the distance of two body's arbitrary points must be constant during time.

The rigid body configurations, is more efficiently defined by rotations and orientations of a system of reference, that defined the orientation matrix, of the body which refers to a fixed one; for this reason rotation and orientation matrix are fundamental algebraic operators which allows to define rigid body configurations, respect other frame of reference defined in the space.



Orientation matrix having for columns the director cosines of $\vec{x}, \vec{y}, \vec{z}$ unit vectors in the ***SoR₁*** system:

$$R_o = \begin{bmatrix} \cos(xX) & \cos(yX) & \cos(zX) \\ \cos(xY) & \cos(yY) & \cos(zY) \\ \cos(xZ) & \cos(yZ) & \cos(zZ) \end{bmatrix}$$

In general, considering two systems of reference ***SoR₁*** $\lfloor o_1, \vec{e}_{x1}, \vec{e}_{y1}, \vec{e}_{z1} \rfloor$ and ***SoR₂*** $\lfloor o_2, \vec{e}_{x2}, \vec{e}_{y2}, \vec{e}_{z2} \rfloor$ (defined by centre and three unit vectors) having the same centre ***O*** $(o_1 \equiv o_2)$, and an arbitrary point ***P*** in the space, the coordinates of ***P*** in both ***SoR₁*** and ***SoR₂*** are given by projection of the vector ***OP*** in the two systems of reference:[1]

$$C_1 = \begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix} = \begin{bmatrix} \langle \vec{e}_{x2}, \vec{e}_{x1} \rangle & \langle \vec{e}_{y2}, \vec{e}_{x1} \rangle & \langle \vec{e}_{z2}, \vec{e}_{x1} \rangle \\ \langle \vec{e}_{x2}, \vec{e}_{y1} \rangle & \langle \vec{e}_{y2}, \vec{e}_{y1} \rangle & \langle \vec{e}_{z2}, \vec{e}_{y1} \rangle \\ \langle \vec{e}_{x2}, \vec{e}_{z1} \rangle & \langle \vec{e}_{y2}, \vec{e}_{z1} \rangle & \langle \vec{e}_{z2}, \vec{e}_{z1} \rangle \end{bmatrix} \begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix} = R_2^1 \begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix}$$

$$C_2 = \begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix} = \begin{bmatrix} \langle \vec{e}_{x1}, \vec{e}_{x2} \rangle & \langle \vec{e}_{y1}, \vec{e}_{x2} \rangle & \langle \vec{e}_{z1}, \vec{e}_{x2} \rangle \\ \langle \vec{e}_{x1}, \vec{e}_{y2} \rangle & \langle \vec{e}_{y1}, \vec{e}_{y2} \rangle & \langle \vec{e}_{z1}, \vec{e}_{y2} \rangle \\ \langle \vec{e}_{x1}, \vec{e}_{z2} \rangle & \langle \vec{e}_{y1}, \vec{e}_{z2} \rangle & \langle \vec{e}_{z1}, \vec{e}_{z2} \rangle \end{bmatrix} \begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix} = R_1^2 \begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix}$$

where C_1 are the coordinates of ***P*** with respect to the ***SoR₁*** and C_2 are with respect to the ***SoR₂*** system, R_1^2 is the rotation matrix that allows to transform the ***P*** point coordinates from the ***SoR₂*** system to ***SoR₁*** system and R_2^1 is the one that expresses the ***SoR₁*** coordinates in the ***SoR₂*** ones.

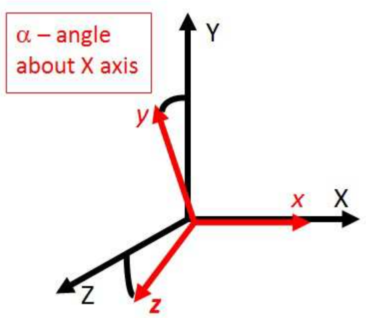
In other words, the rotation matrix has the director cosines of $\vec{x}, \vec{y}, \vec{z}$ unit vectors in the ***SoR₁*** system for columns:

$$R_j = \begin{bmatrix} \cos(xX) & \cos(yX) & \cos(zX) \\ \cos(xY) & \cos(yY) & \cos(zY) \\ \cos(xZ) & \cos(yZ) & \cos(zZ) \end{bmatrix}$$

which expressing the orientation of the ***SoR₂*** with respect to the ***SoR₁***, around a joint *O*.

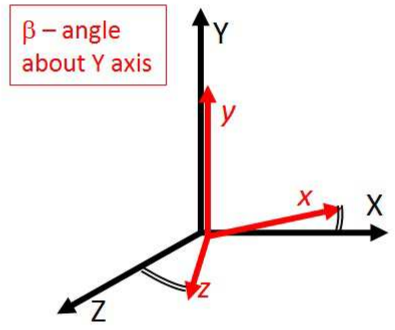
2.1.1 Basic Rotation Matrices

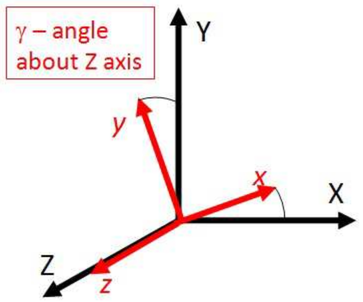
When there is a rotation around a single axis, it is defined by a *basic rotation matrix about one single axis;* obviously it can define three basic rotation matrices:



$$R_x(\alpha) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha) & -\sin(\alpha) \\ 0 & \sin(\alpha) & \cos(\alpha) \end{bmatrix}$$

[1] This notation $\langle\ \rangle$ is used for scalar product: $\langle \vec{u}, \vec{v} \rangle = |\vec{u}||\vec{v}|\cos\theta$

	$R_y(\beta)=\begin{bmatrix}\cos(\beta) & 0 & \sin(\beta)\\ 0 & 1 & 0\\ -\sin(\beta) & 0 & \cos(\beta)\end{bmatrix}$

	$R_z(\gamma)=\begin{bmatrix}\cos(\gamma) & -\sin(\gamma) & 0\\ \sin(\gamma) & \cos(\gamma) & 0\\ 0 & 0 & 1\end{bmatrix}$

2.1.2 Composition of Rotation Matrices

In the majority of cases, it's necessary to represent more complex relations than a basic rotation, therefore the basic rotation matrices can be composed between them, to create a new rotation matrix.

For example, if we make two basic rotations, one on the x axis by an angle α following by another one on the y axis by an angle β, the new rotation matrix can be calculated in the following way:

$$R_T = R_x(\alpha)R_y(\beta)$$

Adopting the same method, is possible to refer non-basic rotation matrix, for example, if there are two moving coordinate frame ***SoR$_i$*** and ***SoR$_j$***, and another one fixed ***SoR$_f$***, with rotation matrices R_i^f and R_j^i, the connection between ***SoR$_f$*** and ***SoR$_j$*** is given by:

$$R_j^f = R_i^f R_j^i$$

In general, the relation among rotation matrices referred to a certain number of coordinate systems can be calculated by:

$$R_{m_n}^{m_1} = R_{m_2}^{m_1} R_{m_3}^{m_2} R_{m_4}^{m_3} \dots R_{m_n}^{m_{n-1}}$$

2.1.3 Rotation Matrix property

Initially, when the two systems are coincident, the rotation matrix is the unitary matrix *I*.

Also, it could be also demonstrate that an arbitrary rotation matrix is orthogonal, in fact $\left(R_n^m\right)^T R_n^m = I$; this means that inverse rotation matrix is equal to the transposed one: $\left(R_n^m\right)^{-1} = \left(R_n^m\right)^T$.

This is a very useful property because it allows to obtain the inverse rotation matrix simply calculating the inverse (or the transposed) of the rotation matrix:

$$R_m^n = \left(R_n^m\right)^{-1} = \left(R_n^m\right)^T$$

Another characteristic of rotation matrix, is the commutative property only for simply rotation around the same axis, in case of multiple rotation about different axes the commutative property doesn't subsist. Therefore, the sequence whereby basic rotation matrix are multiplied among them involves different results, in particular:

- Given any basic rotation matrix ***R***, post-multiplication by ***R*** corresponds to rotations around moving axes *x-y-z*

$$R_{o_{xyz}} = R_x(\alpha) R_y(\beta) R_z(\gamma)$$

- Given any basic rotation matrix ***R***, pre-multiplication by ***R*** corresponds to rotations about fixed axes *X-Y-Z*

$$R_{o_{ZYX}} = R_Z(\gamma) R_Y(\beta) R_X(\alpha)$$

2.2 Euler Angles

One of the methods to select a minimum representation of orientation, consists in three subsequent rotations where the first one and the last one are around the same axis. The rotation sequence to which is conventionally assigned the name of Euler Angles is Z -y'- z'', obtained by post-multiplication, following these steps:

- Rotation on the *Z* axis by the angle φ;
- Rotation on the *y'* axis by the angle ϑ *(y' is the current axis);*
- Rotation on the *z''* axis by the angle ψ *(z'' is the current axis).*

These rotations are referred to the axes transformed by the last rotation done.

2.3 Cardan Angles

Another method consists of a sequence of rotations around each of three axes. Generally, the Cardan angles are obtained by a sequence *Z - x'- y''* (avoiding gimbal lock [2]) on these different moving axes by post-multiplication:

$$R_{o_{Zx'y''}} = R_z(\gamma)R_{x'}(\alpha)R_{y''}(\beta)$$

R_o is obtained by post-multiplication of three basic rotation matrices, with *Z -x'-y''* rotation sequence:

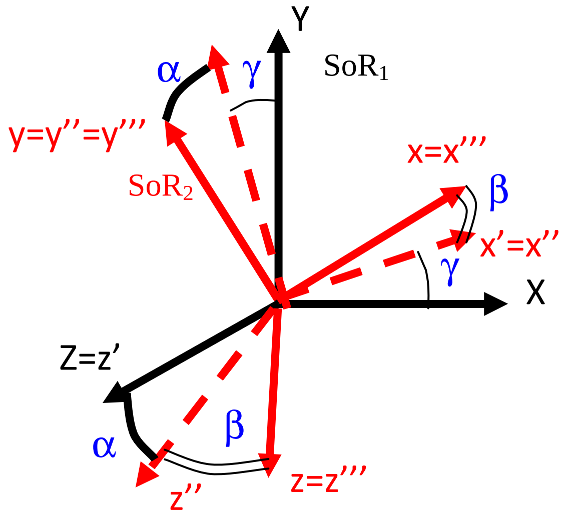
$$R_{o_{Zx'y''}} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} = R_Z(\gamma)R_{x'}(\alpha)R_{y''}(\beta) = \begin{bmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix}$$

$$= \begin{bmatrix} \cos\gamma\cos\beta - \sin\gamma\sin\alpha\sin\beta & -\sin\gamma\cos\alpha & \cos\gamma\sin\beta + \sin\gamma\sin\alpha\cos\beta \\ \sin\gamma\cos\beta + \cos\gamma\sin\alpha\sin\beta & \cos\gamma\cos\alpha & \sin\gamma\sin\beta - \cos\gamma\sin\alpha\cos\beta \\ -\cos\alpha\sin\beta & \sin\alpha & \cos\alpha\cos\beta \end{bmatrix}$$

The three Cardan angles correspond to subsequent rotations that bring the ***SoR*$_1$** to overlap to the ***SoR*$_2$**:

1. Rotation of γ about the *Z* axis (*Z* ≡ *z'*);
2. Rotation of α about the current *x* axis (*x'* ≡ *x''*);
3. Rotation of β about the current *y* axis (*y''* ≡ *y'''*);
4. The *x'''- y''' – z'''* is corresponding to the ***SoR*$_2$.**

[2] Gimbal lock is defined as the loss of one degree of freedom due to the alignment of two spin



Having the γ, α and β angles values, the relative orientation matrix is obtained by replacing values in the $\boldsymbol{R_o}$ final matrix.

The other solution is the inverse approach: given the rotation matrix, the three γ, α and β angles can be obtained by trigonometric solutions of suitable terms. The trigonometric solutions for Cardan angles are:

$$\alpha = \arcsin(r_{32}) \qquad \beta = -\arctan\left(\frac{r_{31}}{r_{33}}\right) \qquad \gamma = -\arctan\left(\frac{r_{12}}{r_{22}}\right)$$

2.4 Euler "aerospace" Angles

Euler "aerospace" angles, called in this way because they are frequently used in aerospace field, defined the RPY convention, where R is *"Roll"*, P is *"Pitch"* and Y is *"Yaw"*. This convention is more interpretable if it is referred of an airplane with a system of reference where the z axis is placed along the fuselage, the y axis is placed along the wingspan and the x axis in according to the right hand rule.

The method consist in three consecutive rotations executed with a $X-Y-Z$ *(Roll – Pitch – Yaw)* sequence about the three perpendicular axes of the original frame:

- Rotation of ψ angle around *Z* axis;
- Rotation of θ angle around *Y* axis (the original one);
- Rotation of ϕ angle around *X* axis (the original one).

The three rotations listed before are obtained from rotation matrices which pre-multiplication the preceding rotation:

$$R_{o_{XYZ}} = R_z(\psi)R_Y(\theta)R_X(\phi)$$

Euler “aerospace” angles correspond to the Z - y' - x'' Cardan angles sequence.

The matrix obtained by pre-multiplication of the three basic matrices, in according to Euler “aerospace” method, is:

$$R_{o_{XYZ}} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} = R_z(\psi)R_Y(\theta)R_X(\phi) = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{bmatrix} =$$

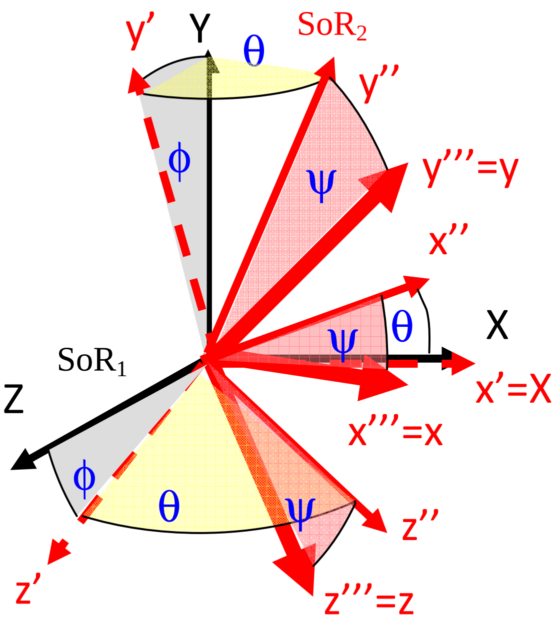
$$= \begin{bmatrix} \cos\psi\cos\theta & -\sin\psi\cos\phi + \cos\psi\sin\theta\sin\phi & \sin\psi\sin\phi + \cos\psi\sin\theta\cos\phi \\ \sin\psi\cos\theta & \cos\psi\cos\phi + \sin\psi\sin\theta\sin\phi & -\cos\psi\sin\phi + \sin\psi\sin\theta\cos\phi \\ -\sin\theta & \cos\theta\sin\phi & \cos\theta\cos\phi \end{bmatrix}$$

Even in this case there are two approaches, the direct and the inverse: the first one allows to obtain the rotation matrix $R_{o_{XYZ}}$ substituting the values of ψ, θ and ϕ angles; with the inverse approach the three angles ψ, θ and ϕ values are obtained by trigonometric solution of suitable terms. The trigonometric solutions for Euler “aerospace” angles are:

$$\phi = \arctan\left(\frac{r_{32}}{r_{33}}\right) \qquad \theta = -\arcsin(r_{31}) \qquad \psi = \arctan\left(\frac{r_{21}}{r_{11}}\right)$$

The three Euler “aerospace” angles correspond to subsequent rotations that bring the ***SoR₁*** to overlap to the ***SoR₂***:

1. Rotation of ϕ about the fixed *X* axis (Ex: 30°)
2. Rotation of θ about the fixed *Y* axis (Ex:80°)
3. Rotation of ψ about the fixed *Z* axis (Ex: -30°)
4. The *x’’’* – *y’’’* – *z’’’* is corresponding to the ***SoR₂***



2.5 *Protocols in literature*

In literature there are many protocols for recording data using the optoelectronic system, some of these are:

- **Davis**: 1980, Davis, New York, USA 20 markers;
- **Helen Heyes (Lower Limbs)**: 1990, Vaughan, New York, USA 15 markers;
- **SAFLo**: 1995, Frigo, Politecnico di Milano, Italy 25 markers;
- **CAST**: 1995, Cappozzo, Istituto Rizzoli, Bologna 28 markers.

Each of these protocols has a specific approach and its characteristics, in particular, the main differences among them are: numbers of markers, body segments involved, applications and capacity of 3D representation. It would be very interesting analyze all of protocols in details, but this discussion is not strictly necessary for this work. Therefore the description will be limited on the Davis protocol, which is one of the most commonly used in clinic.

The Davis protocol uses in total 20 markers of which 15 are placed on lower limbs: the markers 1,2 and 3 (refer to the figures below) defines the position of the foot in 3D space. Thanks to markers labeled with numbers 3,4, and 5 , it's possible to create a ***uvw*** reference systems which can allow to predict the position of ankle and toe.

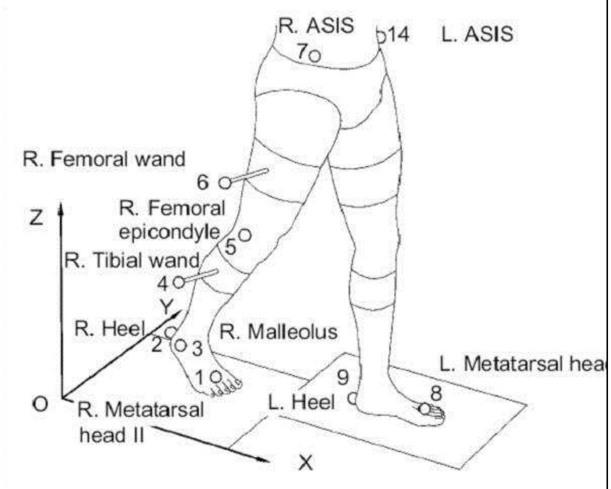


Fig 10: Markers position on David protocol (anterior view)

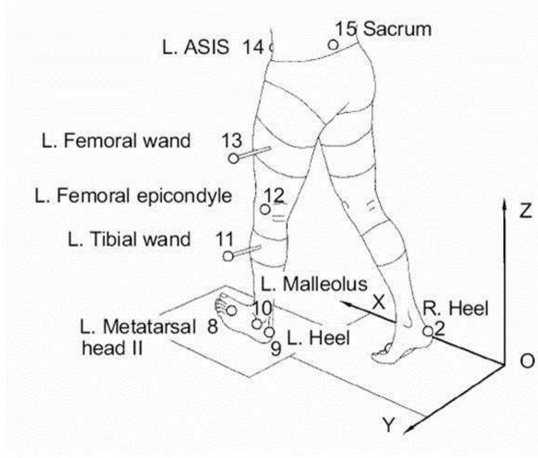


Fig 11: Markers position on David protocol (posterior view)

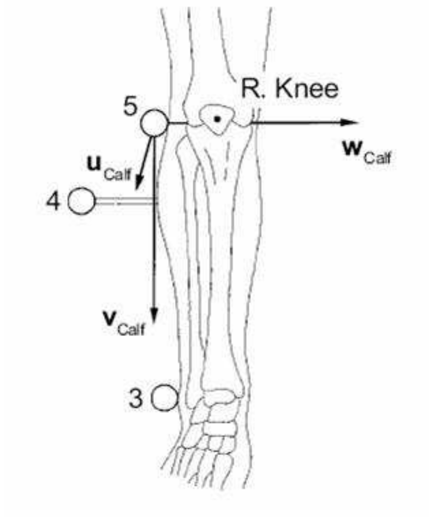


Fig 12: Markers to define 3D calf position

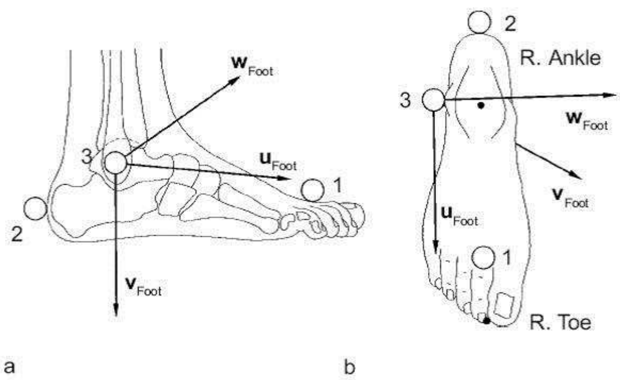


Fig 13: Markers to define foot position.

The ***uvw*** reference systems can be used in specific prediction equations (based on anthropometric dimensions data) to estimate the positions of anatomical points. The Davis protocol defines also the segment reference frames positions and orientation: they must be embedded at the centres of gravity of each body segment with a defined orientation for each axis. The method used to calculate relative anatomic angles, is easier to explain with an example, as left knee's rotation axis:

There are three separate ranges of motion:

1. Flexion and extension take place about the mediolateral axis of the left Thigh (Z_2);
2. internal and external rotation take place about the longitudinal axis of the left calf (X_4);
3. abduction and adduction take place about an axis that is perpendicular to both Z_2 and X_4.

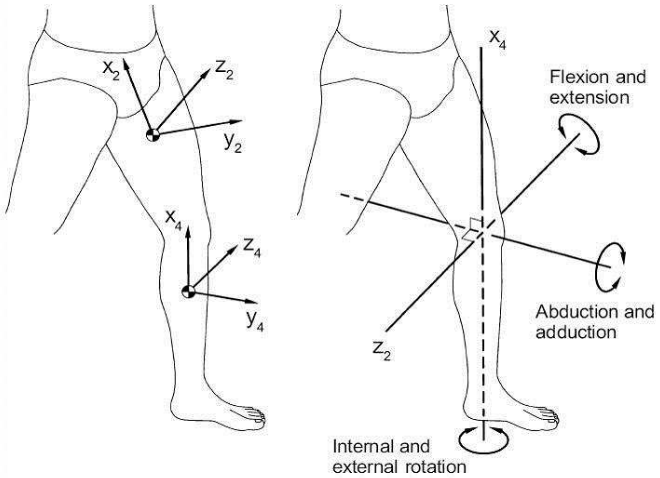


Fig 14: Axes of rotation for the left knee

Note that these three axes do not form a right-handed triad, because Z_2 and X_4 are not necessarily at right angles to one another.

The corresponding abduction and adduction unit vector is calculated by vector product of corresponding unit vectors of Z_2 and X_4 axes:

$$\vec{y}_{Ab-Ad} = \frac{\vec{z}_2 \otimes \vec{x}_4}{\left|\vec{z}_2 \otimes \vec{x}_4\right|}$$

Anatomical joint angles can be calculated thanks to the formulas of the inverse approach applied at the Euler resolution angles. Moreover is possible calculate Euler angle for segment absolute orientation, even in this case is more simple explaining this with an example as define orientation of the right calf's reference frame relative to the global system of reference XYZ:

The three angular degrees of freedom (or Euler angles ϕ_{Rcalf}, θ_{Rcalf}, and ψ_{Rcalf}) defining the orientation of the right calf's reference axes (x_{Rcalf}, y_{Rcalf}, and z_{Rcalf}) relative to the global reference system XYZ. Note that the calf's CG has been moved to coincide with the origin of XYZ.

The three Euler angle rotations take place in the following order:

(a) ϕ_{Rcalf} about the Z axis;

(b) θ_{Rcalf} about the line of nodes;

(c) ψ_{Rcalf} about the z_{Rcalf} axis.

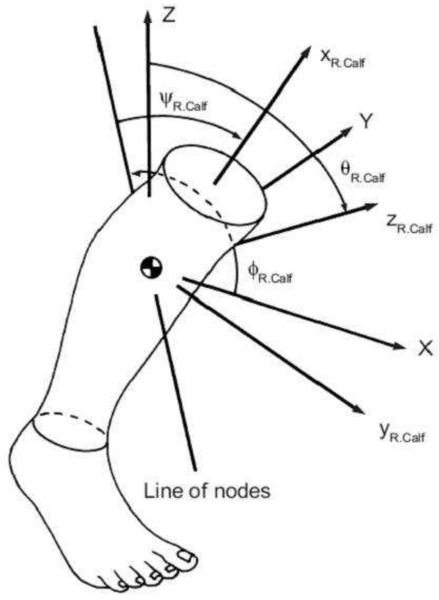


Fig 15: Coordinate system of the right calf

CHAPTER 3

Xsens Technology

3.1 Introduction of Xsens technology

Xsens Technologies is a developer of 3D motion tracking products, based on inertial sensors manufactured with MEMS technology. The Xsens product used in these work is the MTw™ is a miniature wireless inertial measurement unit (IMU). It is a small, lightweight and completely wireless 3D motion tracker, formed by 3D linear accelerometers, 3D rate gyroscopes, 3D magnetometers and a barometer (for pressure measurement). This product returns 3D orientation, acceleration, angular velocity, static pressure and earth-magnetic field intensity. The MTw™ has an embedded processor that handles sampling, calibration, buffering and strap down integration of the inertial data, it also controls the wireless network protocol for data transmission. Wireless transmission is created and maintained by the (patent-pending) Awinda™ radio protocol. This feature can handle up to 32 MTw™ IMU and the accuracy of 3D motion tracking is maintained in case of a temporary loss of transmission data. Awinda™ station, using the Awinda™ radio protocol, enables an initially data sampling at 1800 Hz but this involves too many data for wireless transmission and, generally, a too heavy computational load on a typical host device. Therefore the MTw™ processor down-sampling data at 600 Hz, with Step Down Integration (SDI) the data is transmitted to the Awinda station and, finally, on the PC using USB interface.

Fig 16: Motion traker Xsens MTw™

Fig 17: the Xsens Awinda station

The sample rate can be chosen by the user but it depends from the numbers of linked sensors: the user can choose a sampling rate up to 150 Hz using one MTw™, with more than one sensor, the sampling rate will proportionally decrease according to the number of devices (e.g. with 5 connected MTw™ the maximum sample rate is 75Hz). Awinda station allows to use up to two input synchronization signals and two output synchronization signals, moreover user can decide which type of synchronization to implements in according to his systems. Another important characteristic of Awinda station is that power supply is only needed for charging MTw™, for updating its firmware and to reactivate the MTw™ if it has been switched off at the end of last utilization. A fundamental feature is that for Xsens MTw product, the USB power is enough for wireless communication, both for measurement and recording, indeed it's worth remembered that each MTw™ has a LiPo battery with a capacity of 220mAh which ensures 2.5-3.5 hours of run-time [3].

The body straps are a quick and comfortable solution for fixing the MTws™ to the subject/patient's body. Each MTw™ is equipped with a special click mechanism that allows quick and safe connection to the strap.

Fig 18: MTw™ click mechanism

Fig 19: MTw™ click-in body straps

3.2 Xsens coordinate systems

Each MTw™ has a right handed fixed coordinate system, that defines the sensor coordinate frame ***S*** (refer to the figure below). This frame is aligned with the sensor's external box but the real reference is inside and, of course, this may cause an error and a loss of accuracy. Moreover the alignment between the coordinate system ***S*** and the bottom of the MTw™'s box is guaranteed less within than 3°. Another problem of the inertial sensors in the orthogonality of the reference system's axes, but regarding Xsens MTw™ the non-orthogonality is less than 0.1°. In default conditions each MTw™ returns angles between the coordinate system ***S*** and the "Earth" coordinate system ***E***, with ***E*** as reference coordinate system. ***E*** coordinate frame

[3] MTw™ User Manual data

is called "Earth" because it is "created" by Earth with its magnetic field and its gravity acceleration axis, it is defined as a right handed coordinate system as follows:

- *X* axis has the same direction and orientation of a vector that pointing to the Earth magnetic North;
- *Y* axis is calculated in according to the right hand rule;
- *Z* axis has the same direction of gravity force but opposite orientation.

The ***E*** coordinate system is clearly invariable, therefore to perform a clearly and more intuitive description of the reset operations, it has been created a new coordinate system called *Fixed coordinate system* ***F***. Hence ***F*** is taken as the reference coordinate system and in default conditions coincides with ***E***:

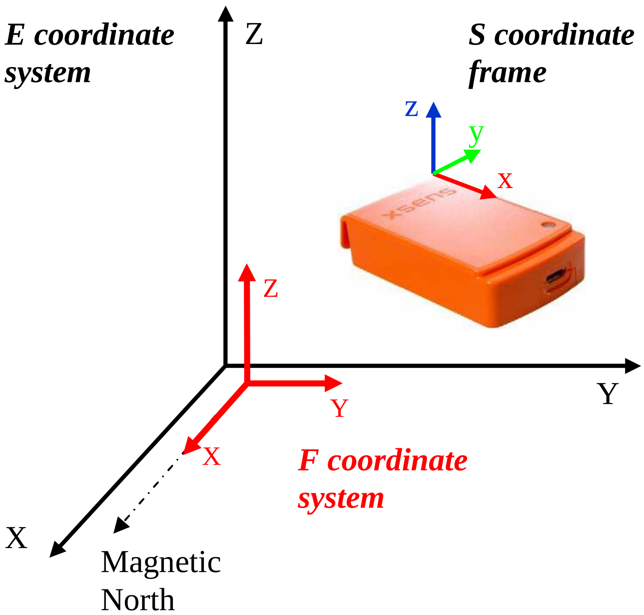


Fig 20: MTws™ Coordinate systems

3.2.1 Orientation Output Modes

The Xsens Technologies has implemented three orientation output modes [4]:

1. Unit quaternions;
2. Euler "aerospace" angles: Roll, Pitch and Yaw;
3. Rotation Matrix elements

The quaternions are defined as the quotient of two vectors and can be represented as the sum of a scalar and a vector or as a vector with a complex part. The main advantage of this

[4] In according to the right hand rule, the positive rotations are the counter clockwise rotations

representation is the absence of singularity: on the contrary this problem is present in the Euler “aerospace” angles and in the rotation matrix representations (in this last case it is possible to avoid singularity with a particular angle resolution).

The Euler “aerospace” angles mode, returns three angles called *Roll, Pitch* and *Yaw* following the theory explained in the 2.4 paragraph.

The third representation is the rotation matrix elements: as output there are the entries r_{ij} $\forall i, j \in [1,3]$ that make up the matrix. Following the theory explained in the 2.4 paragraph is possible to calculate the Euler "aerospace" angles after reconstructing the matrix starting from the entries in output.

Each of these data, independently of its representation, is returned at every sample.

3.2.2 Orientation Reset

The default settings of the MTw™ can sometimes be strictly, therefore four different orientation reset were implemented by Xsens. These reset procedures to set different reference coordinate systems distinguished by the ***E*** coordinate system. The reset can be performed for all sensors or for a selected sensor, therefore this option leaves the user free to decide if and which reset to perform for each sensor.

3.2.2.1 Arbitrary Alignment

The first type of reset is called *Arbitrary Alignment*, used to change the sensor coordinate system ***S*** in another known coordinate system. For example, should it be necessary to obtain in output data referred to a given object coordinate system, using the *Arbitrary Alignment* is sufficient to create a rotation matrix R_S^O which changes the sensor coordinate system ***S*** into the object coordinate system ***O***:

$$R_S^O = R_S^F \left(R_O^F\right)^T$$

When this reset is applied, orientation data are given between the object coordinate frame ***O*** (obtained from the changed sensor coordinate frame) and the *Fixed coordinate system* ***F***.

3.2.2.2 Heading Reset

The second type of reset is called *"Heading Reset"*: it is useful when it is necessary to change the ***S*** coordinate system while keeping *Z* axis pointing upward and varying only the *X* axis direction.

After the *Heading Reset*, the ***F*** coordinate system is changed in a new Fixed frame called ***F'*** characterized by:

- *X* axis pointing in the same direction of the *X* axis of the selected Xsens sensor
- *Y* axis in according to right hand rule
- *Z* axis pointing upwards (parallel and opposite to gravity)

An important factor to know is that the *Heading Reset*, both the orientation and magnetic data will be returned with respect to ***F'*** and the first output data will be:

Roll = previous value	Pitch = previous value	Yaw = 0°

The returned angles identifying the rotations needed to take ***F'*** to overlap to ***S***.

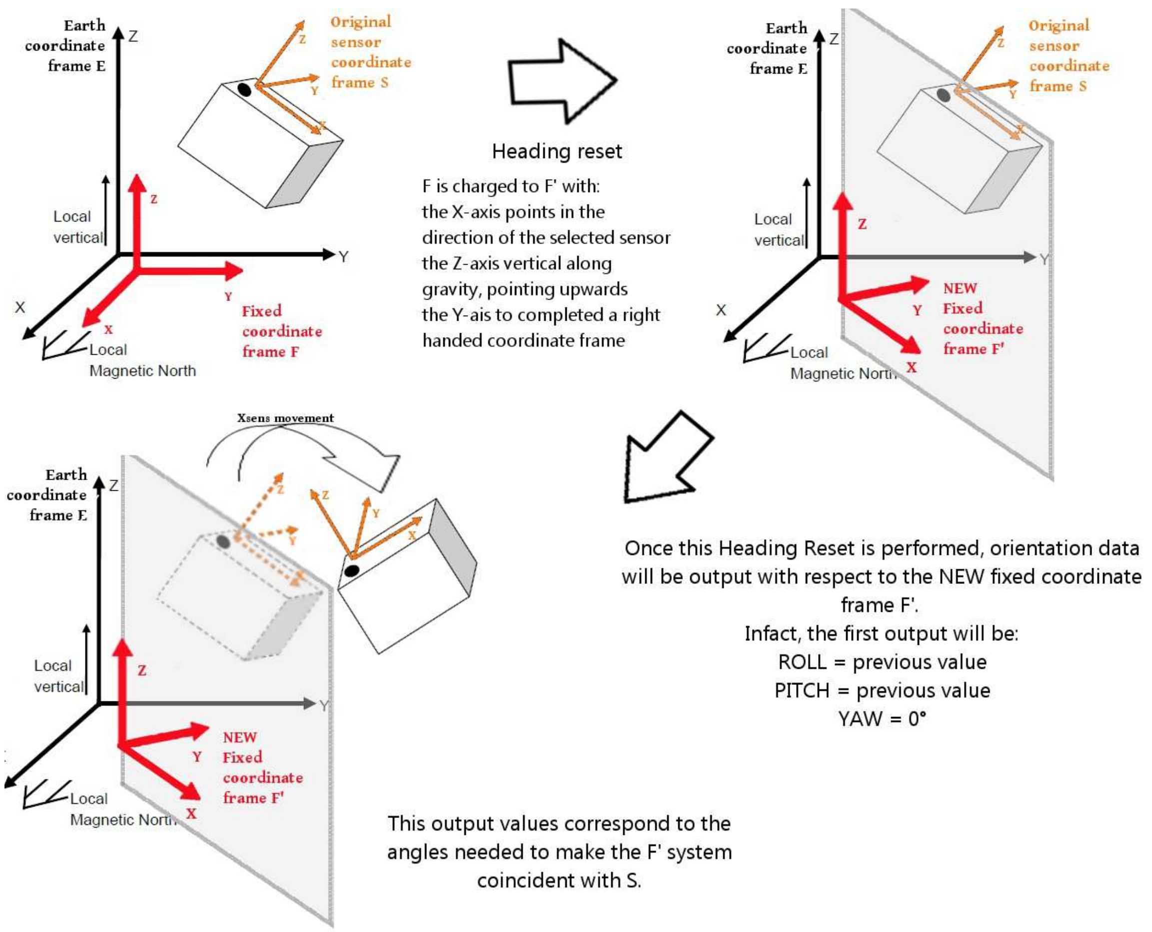


Fig 21: Stages of Heading Reset

3.2.2.3 *Object Reset*

The third type of reset is called *Object Reset*: it is very useful when the sensor coordinate system must be the same than an object's coordinate system. After attaching the sensor to the object and after the *Object Reset*, the sensor coordinate system ***S*** changes to ***S'*** and chosen with:

- *X* axis is projected on the new horizontal plane;
- *Y* axis in according to right hand rule;
- *Z* axis pointing upwards.

Once *Object Reset* is conducted, orientation data will be output with respect to the new sensor coordinate system ***S'***, therefore the first output will be:

Roll = 0°	Pitch = 0°	Yaw = previous value

These angles correspond to the rotations needed to bring ***F*** to overlap to ***S'***.

Note: if the *X* axis of ***S*** frame is about at 90° with respect to the horizontal plane, the *Object Reset* may not work because the projection of *X* axis is not is not clearly defined.

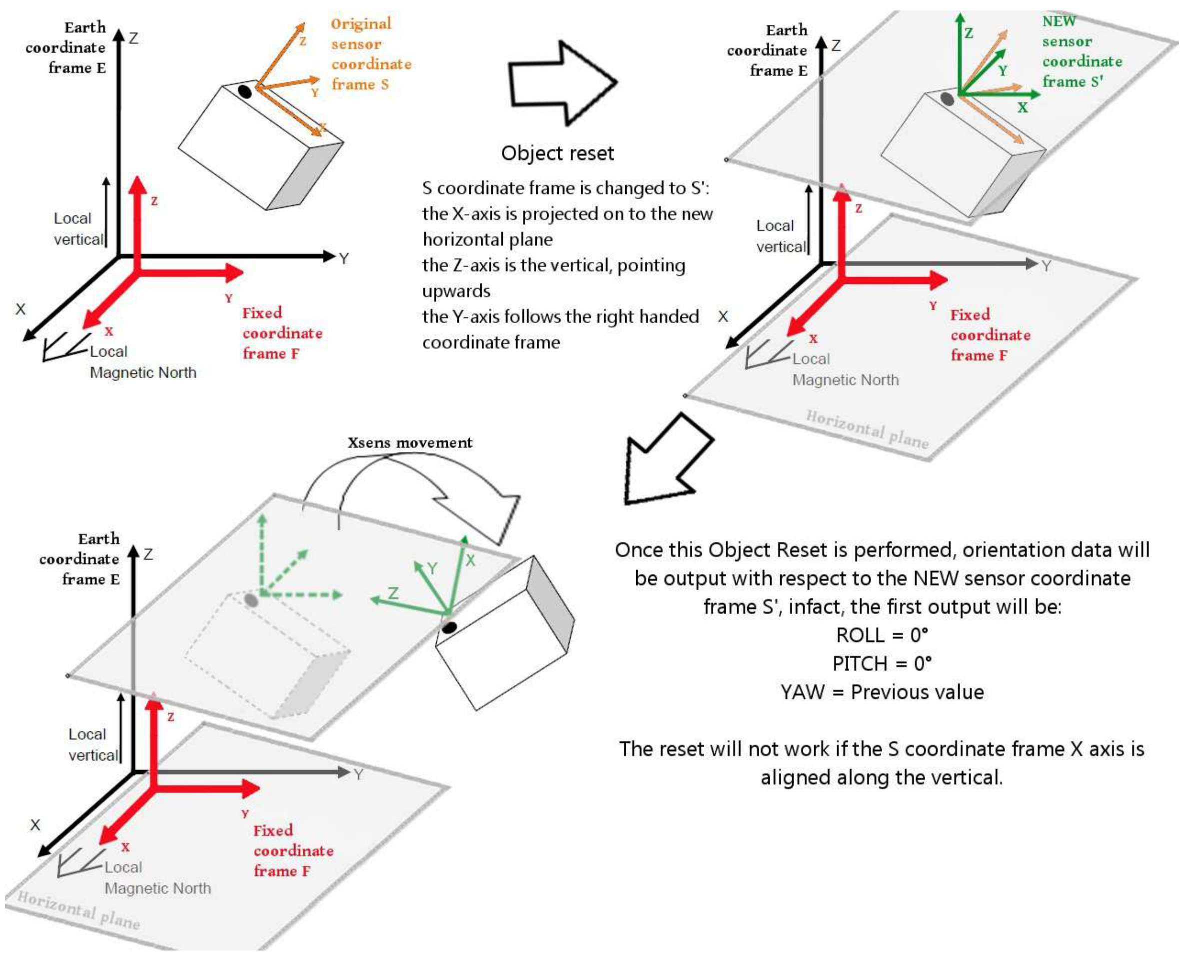


Fig 22: Stages of Object Reset

3.2.2.4 Alignment Reset

The fourth type of reset is called *Alignment Reset* and it is the most complete reset of MTw™. It combines the *Object Reset* and the *Heading Reset* in a single time. When the *Alignment Reset* is performed, both to ***S*** and ***F*** coordinate systems are changed in the new ***S'*** and ***F'*** coordinate systems. The first change is done due to the *Object Reset* and the second due to the *Heading Reset*. After the *Alignment Reset* is performed, orientation data will be output with respect to the new Fixed coordinate system ***F'***, and output angles represent the rotation needed for bringing ***F'*** to overlap ***S'***. The first output after the *Alignment Reset* is:

Roll = 0°	Pitch = 0°	Yaw = 0°

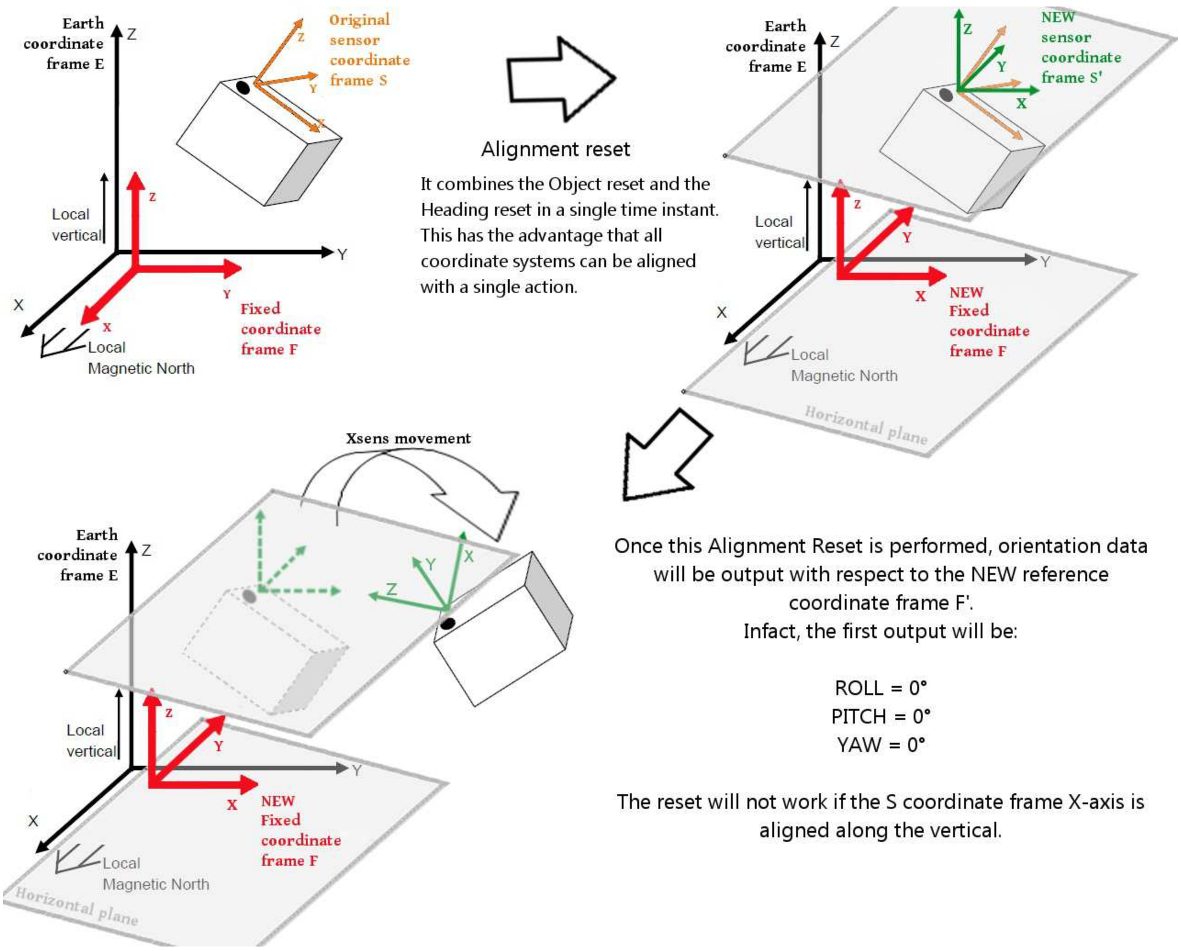


Fig 23:Stages of Alignment Reset

These reset could make more adaptable and comfortable using the Xsens MTw™: however, at the beginning, these reset were not at all intuitive to use because the user manual had a very poor description of this argument not very clear, in particular for the used notations.

3.2.3 MT Manager Xsens Software

The MT Manager is the software that manages connections between Awinda station and MTws™ and also it visualizes, records and extracts data from MTw™. This software also allows to perform reset, to select the output orientation mode and the data that will be output by the software. Moreover the MT Manager performs real time 3D visualisation of: orientation data (*Roll*, *Pitch* and *Yaw* angles or MTw™ position in the 3D space), and both inertial and magnetic data (acceleration, angular velocity and magnetic field intensity).

Xsens Technologies has developed the MTw™ Software Development Kit (SDK) that gives full access to all data and configurations of the MTw™.

3.3 Considerations about the use of Xsens

One of the most important targets of motion analysis is recording the skeleton's movements, with the minor possible disturb possible. And other movement, like the skin and muscle contraction effects, are considered artefacts. The optoelectronic system uses reflective markers to identify movements, and these markers are placed on "anatomical landmarks" where skin and muscle artifact are minimum. With respect to the MTws™ positions, for obvious reasons, it's impossible to place them on "anatomical landmarks", therefore in each recording sessions there will be skin and muscle effects. It is possible to define the best points to place body straps with MTws™, like the wrist for forearm movements and the lateral side of to Shank when considering the lower leg movements: but these are simple considerations to avoid large artefacts due, for example to the calf muscles.

Other artefacts can be due to body straps movements: markers are attached to the body with biocompatible tape. However MTs are positioned thanks to the straps and, to avoid slippage during movements, they have, on the interior side, two antislip bands. Despite these solutions, body straps movements or slippage may be present, and it is necessary to consider a possible error due to these effects.

3.4 Angles definitions and conventions

In this work, different typologies of angles will be considered: the BTS optoelectronic system uses Cardan angles where as the Xsens uses the Euler "aerospace" angles, as well as both technical and physiological angles will be introduced. For this reason, an angle's conventions has been adopted to make data analysis simpler and more clear.

The first definition adopted concerns the difference between Xsens which adopt Euler "aerospace" angles and Optoelectronic BTS system which uses Cardan angles:

- Euler "aerospace" angles adopted from Xsens, will be indicated with uppercase notation:

  Φ = Roll Θ = Pitch Ψ = Yaw

- Cardan angles used by Optoelectronic BTS system, will be indicated with lowercase notation:

  ϕ= Roll θ = Pitch ψ = Yaw

By after adopting this convention is possible to identify the typology of angles and what is the system to which they are referred.

During the tests it a particular posture was used, called ***physiological reference position*** which identify the standing position of the subject. Moreover some angles with particular property, both technical and physiological were defined:

1. ***Reset angle***: this angle is used during Xsens reset to obtain a defined orientation of the *X* axis with respect of the horizontal plane;
2. ***Static angles***: these are output angles referred to the physiological reference position (static position);
3. ***Segment angles***: by this definition angles detected by Xsens during movements and referring to the physiological reference position are indicated. They will be indicated with one subscript identifying the segment that has generated the angles (e.g. Φ_T, Θ_T, Ψ_T are Roll, Pitch and Yaw angles calculated between Thigh and the physiological reference position);
4. ***Segment to Segment angles***: these angles are calculated by MTw™ or the optoelectronic system between two body segments (e.g. movements of Shank with respect to Thigh). They will be indicated with two subscripts identifying two segments, between which are calculated these angles (e.g. φ_{TS}, θ_{TS}, ψ_{TS} are Roll, Pitch and Yaw Thigh to Shank Cardan angles and Φ_{ST}, Θ_{ST}, Ψ_{ST} are Shank to Thigh Euler "aerospace" angles);
5. ***Joint angles***: by this definition physiological/anatomical angles are indicated. They must be calculated about coordinate system that must be based on bones' movements, called joint coordinate systems. In this work, the joint angles will be indicated with a single subscript to identify the joint to which these angles are referred.

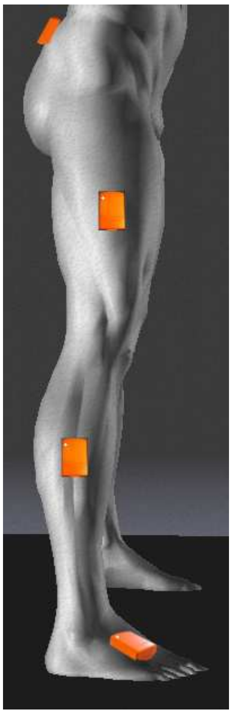


Fig 24: Static angles

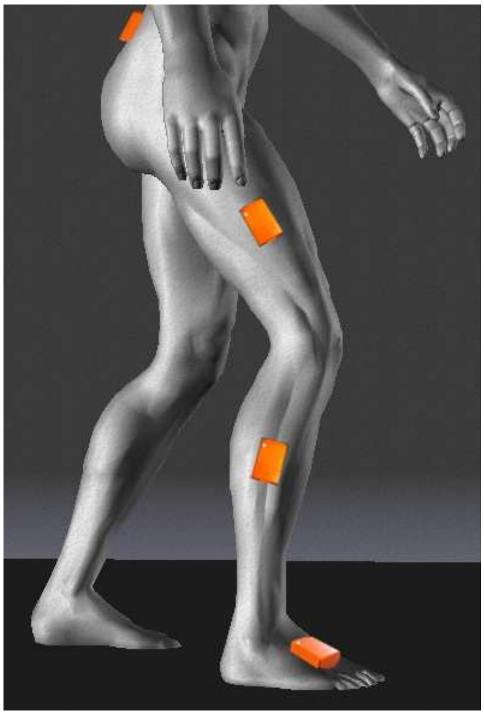


Fig 25:Segment angles

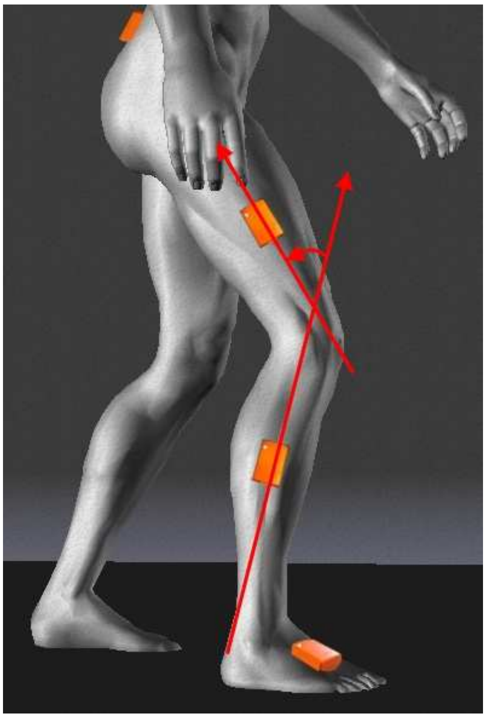


Fig 26:Segment to Segment angles

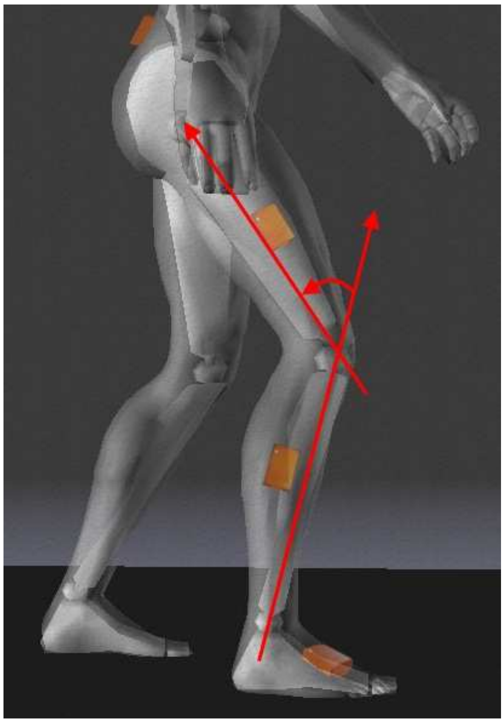


Fig 27: Joint angles

The *Segment to Segment angles* and the *Joint angles* curves recorded during a session trend, strictly depends on the reference coordinate system. In the gait analysis, if the Shank coordinate system is taken as reference, the rotations that is coordinate system has to do to coincident with the Thigh's coordinate system are the angles values returned; on the contrary, if when the Thigh is taken as reference, its coordinate system will be the moving one.

Obviously, for this reason, the plots of the obtained graphs corresponding shell be of opposite sign, because the coordinate systems rotations are the same but performed in opposite direction.

In this work, the coordinate system that return the angles in the standard physiological conventions will be always taken as reference.

CHAPTER 4

Pilot tests

4.1 Preliminary considerations

The aims of this work is to understand the MTws™ operation and to try developing, a method for performing the best recording of motions; parallel to this, to create a software to analyze the data is also an objective. The aims can be schematized with the four targets of this work:

1. To create a method for performing motion capture and motions analysis with MTw™ developed by Xsens Technologies;
2. To evaluate the accuracy of Xsens when compare to optoelectronic systems;
3. To use the Xsens angular velocity data for calculating the joint's axis of movement during single motions (e.g. flex-extension or intra-extra rotation) and defining a joint anatomical coordinate frame;
4. To develop a software for analyzing and processing the data.

Regarding the first target, it was necessary to decide whether to perform a reset, or to use the default coordinate system (Earth) as reference system. After a long set of tests, it was decided to perform the *Alignment Reset* in a novel way that was named "*Alignment Reset Pack*": this reset is performed after have positioned the MTws™ closer to each other, to form a "pack" (stack up).

The "*Alignment Reset*" with a "pack" configuration resulted more convenient for two reasons:

- after performing an "*Alignment Reset Pack*", each MTw™ has the same new coordinate system ***S'*** and it will refer to the same new reference frame ***F'***;
- When the MTws™ are placed on the subject/patient's body in the physiological reference position, the angles obtained between this position and the sensors reset position, named as *Static angles*, give information about how sensors were placed on

the body. These angles can also give information about the static position of the subject/patient, and can highlight postural disorders.

Regarding the second aim of the study, it could be considered the most important, because the optoelectronic system is nowadays the most used system in clinical and sport area when performing motion analysis. This system is very accurate and, nowadays, is considered the golden standard for the analysis of motion.

Regarding the third target, the data analysis step will be fully explained in the 6.1 paragraph. These theoretical considerations need to be verified by preliminary tests.

4.2 Preliminary tests

Preliminary tests were necessary for deciding which hypothesis were wrong. They allowed the resolution of problems and improve the methods.

4.2.1 Battery life test

To program a field test, the real time of discharge of battery is a fundamental variable: therefore a test for evaluating the discharge time of MTws™ was performed. This test was made following the worst case: this is when all sensors working in acquisition mode. The test was performed with sensors that had different percentage of initial charge. Thanks to this differences was possible to determine if different initial charge may have affected the discharge rate, evaluating the slopes of discharge curves.

During the tests, also the discharge time of the netbook's battery (that should have been lasting longer than the MTws™) was evaluated. How it's possible to note on the figure 28, only the curve of the 438 sensor had a lower slope than the others: this means that discharge time speed is independent from starting charge.

Moreover, time discharge time difference between 438 and 440 sensor was about 10%.

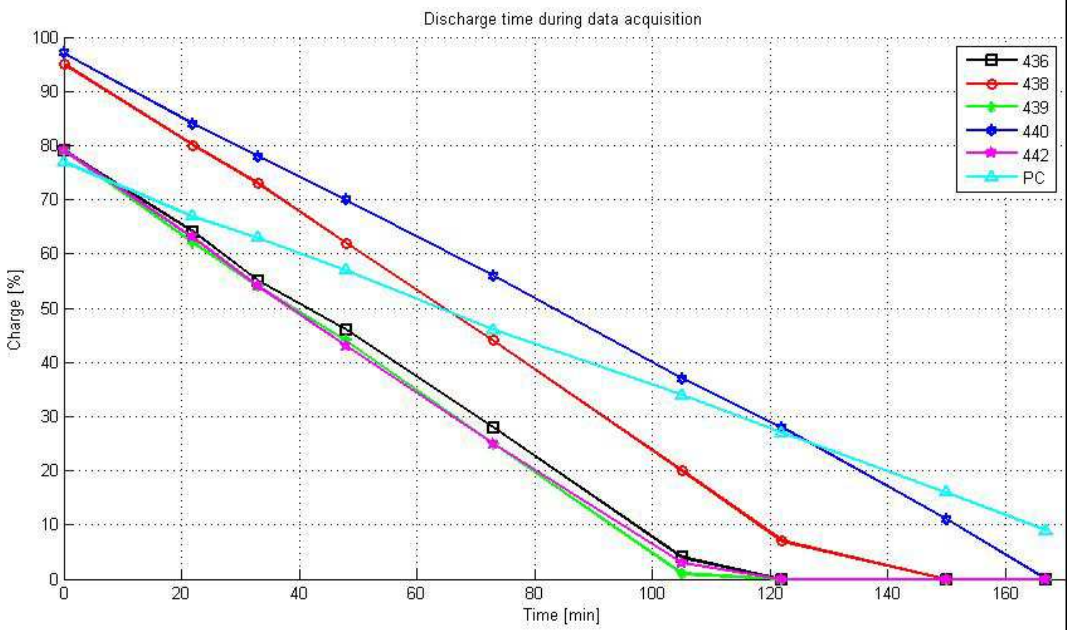


Fig 28: MTws™ discharge time

Finally the approximate battery life in normal conditions, during acquisition was estimated between 2.30 – 2.45 hours from an initial 100% charge state.

4.2.2 Magnetic field test

Another preliminary test for understanding the MTws™ features was performed with the following aim: evaluating the influence of aluminium (paramagnetic material) on the Xsens' magnetometer.

During this test, both the 442 and 436 sensors were placed on two aluminium bars, the *Alignment reset* was performed to sensors 442, whereas no reset was performed on sensor 442. This different approach can show possible differences of electromagnetic interaction of the sensor to which the reset was performed with respect to the other sensor.

Initially both sensors need a short time to stabilize themselves. At the end of this transient period, it has been possible to appreciate a low interference due to aluminium and a good stability of the sensors. You may notice in the chart below that the Z axis was the less stable and that the sensor 442 (with the *Alignment Reset*) has given in output values between -4.6° and -0.5°, while for sensor 440 (without reset), the values range is between -69.04° and -72.36°.

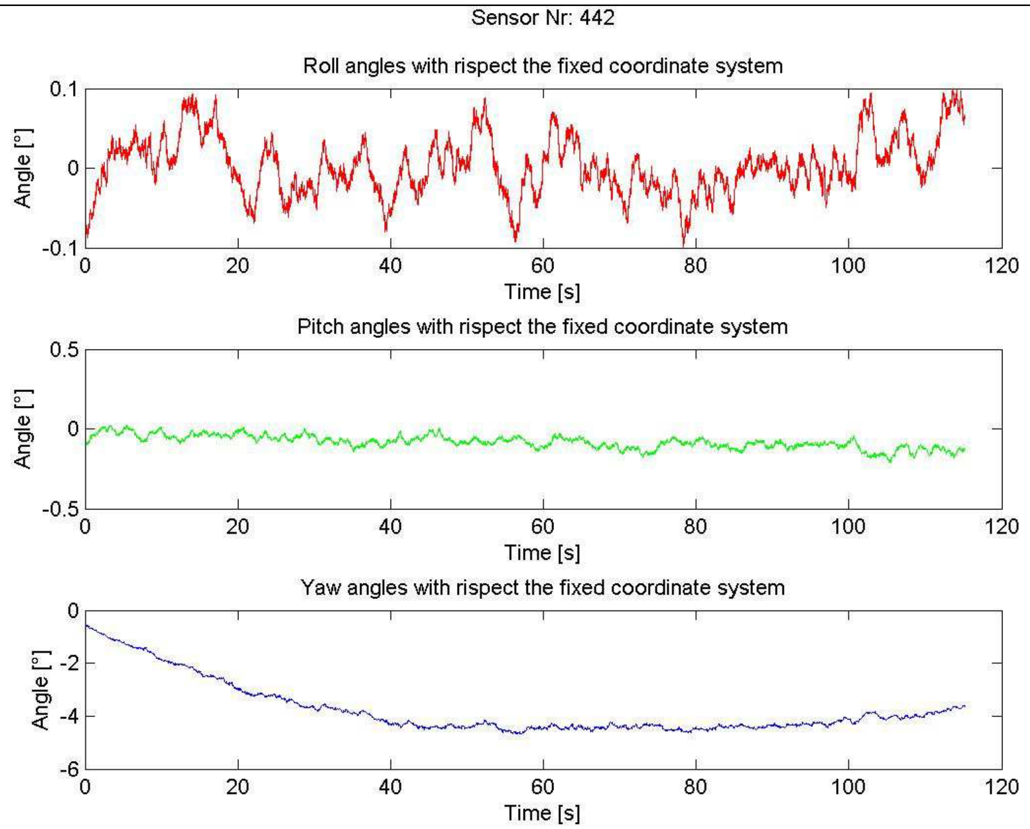


Fig 29:Sensor 442 angles

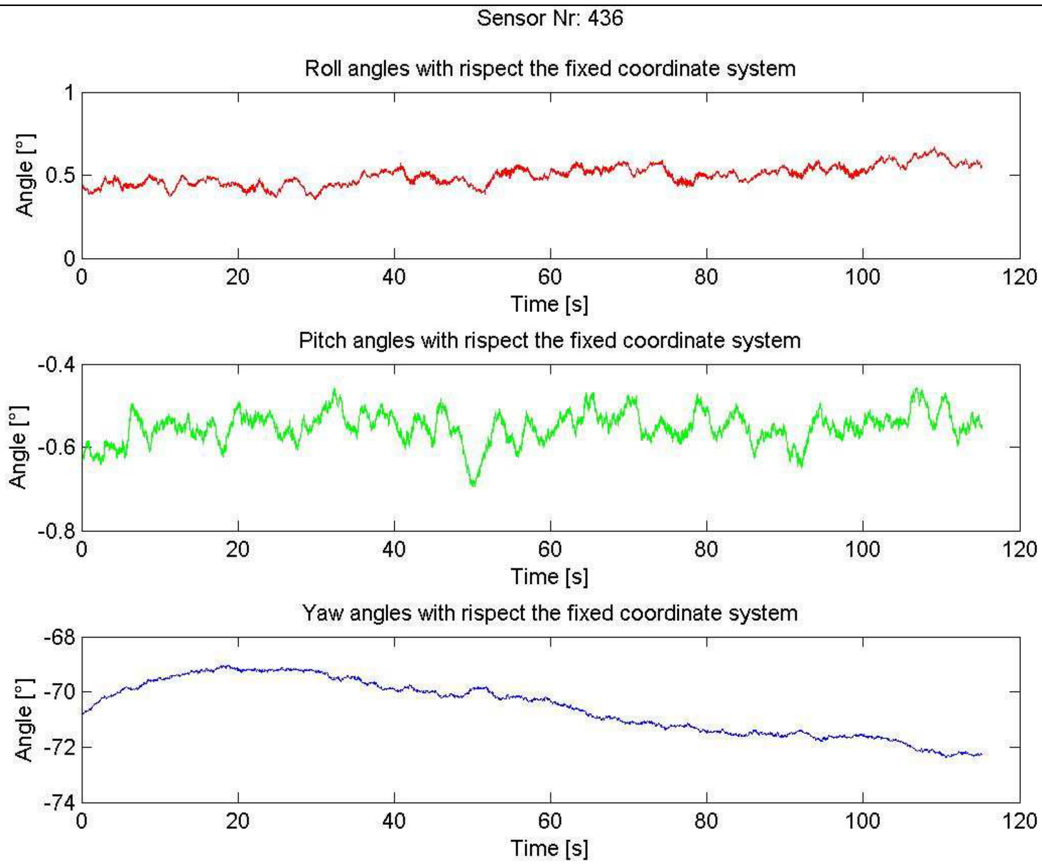


Fig 30: Sensor 436 angles

This test highlighted limited and a comparable variations of the angles, possibly due to the aluminium bar nearby. However only the Yaw angles had variations higher than 1°, and they are limited to about 4°; therefore the aluminium hasn't a strong influence on the MTws™.

4.2.3 Pilot ski tests at the Cermis ski area

The first field test was planned to study several cross country skiing techniques. The test was performed the 4th of April at the Alpe Cermis (TN), using 5 MTws™ produced by Xsens Technologies. Snow was very soft due to a subtle rain in the second part of the morning, with a temperature about 8°C.

The subjects were three cross country professionals, two men and one woman:

Subject	Sex	Weight	Height	Status
Z.C.	Man	184 [cm]	78 [Kg]	Active
V.A.	Man	181 [cm]	80 [Kg]	Active
B.E.	Woman	158 [cm]	52 [Kg]	Not Active

The test was divided in two parts: the first part was a snowplough braking technique test, the second was a cross-country skiing technique test (with a basic calibration of body segments).
First of all, the biggest problem to solve, was to avoid wetting the Xsens sensors, and, at the same time, fixing the sensors to the ski with the best stability. It was decided to fix two sensors to the ski, because the researched data during this test where the angles formed by the skier (respect the parallel ski position) during the snowplough braking technique and the acceleration corresponding. Xsens was coated with a transparent film, for a basic, waterproof pack. To avoid possible hole or infiltrations through this thin material, both Xsens were covered with duct tape. So a small, but strong, waterproof package was obtained.

Fig 31: Xsens position on the ski

As reference point the boot binding was taken. Doing this all sensors were placed in the same position for all subjects, independently from the different equipment and the subject's body characteristics. The Xsens were fixed with the duct tape in the anterior part (from boot tip to ski tip) of ski: the first sensor (cod. 438) at a distance of 175 mm and the second one (cod. 442) at 240 mm from the binding. These positions were safe for the sensors and were characterized by high stability on the ski; the distance, as you can see in the picture, "was forced" due to boot binding size.
Two different types of measurement system setup were defined:

Measurement System Setup 1			
Sensors	Sensors position	Orientation reset	Fs [Hz]
438	17,5cm of boot binding (X>0 Xsens system frame)	Alignment reset	120
442	24 cm of boot binding (X>0 Xsens system frame)	Alignment reset	120

Measurement System Setup 2			
Sensors	Sensors position	Orientation reset	Fs [Hz]
438	The same of MSS 1	Alignment reset	120
442	The same of MSS 1	No reset	120

- The *Alignment Reset* was performed when skier was in the start position, with parallels skis. This allows to obtain directly the angle between skis' reset position and skis' position during snowplough braking;
- No reset means Xsens data will be output respect the Earth system of reference.

The presence of two sensors allowed to obtain the data regarding the angles from 438 sensor and the acceleration/angular velocities from sensor 442. Lastly, to complete subject's equipment, the netbook and the Awinda Station were placed in a small backpack, worn by each subject during the test. The Awinda station in the backpack was always close to the sensors, with a lower possibility of loss of signal and data.

Fig 32: Subject with equipment

Fig 33: Detail of Xsens on the ski

Snowplough braking technique tests were performed like this:

1. The subject stood with parallel skis, in the start position;
2. *Alignment reset* was performed, according to the MSS type;
3. The recording was started with the MT manager software and the PC was inserted into the backpack;
4. The subject began the descent pushing along the first 10/15 metres, then he continued with parallel skis, finally he concluded with snowplough braking technique;
5. The recording was stopped with subject stood in the snowplough brake position.

This test was performed for both left and right ski for every subject, with different measurement system setup, like synthesizes the following table:

Test Nr.	**Subject**	**Starting time**	**MSS**	**Sensor position**
0	Z.C	10:35	1	Right ski
1	Z.C	10:39	1	Right ski
2	Z.C	10:40	1	Right ski
3	Z.C	10:42	1	Right ski
4	Z.C	10:54	2	Left ski
5	Z.C	10:56	2	Left ski
6	Z.C	10:58	2	Left ski
7	V.A.	11:02	2	Left ski
8	V.A.	11:04	2	Left ski
9	V.A.	11:06	2	Left ski
10	V.A.	11:09	2	Right ski
11	V.A.	11:10	2	Right ski
12	V.A.	11:12	2	Right ski
13	B.E.	11:27	2	Right ski
14	B.E.	11:29	2	Right ski
15	B.E.	11:31	2	Right ski
16	B.E.	11:34	2	Left ski
17	B.E.	11:36	2	Left ski
18	B.E.	11:38	2	Left ski

Fig 34: Alignment Reset and start recording

Fig 35: 10/15 m of parallels ski descent

Fig 36: Snowplough braking step

Fig 37: Stop recording

The second part of the test was formed by two operations:

1. Calibrations of subjects' body segments
2. Acquisition of cross-country skiing technique

These two topics can be exposed separately without modifying the linear development of this work, indeed the calibrations of subjects' body segments can be interpreted as a successive step: so, for continuity and clarity of exposition, it will be explained in the chapter 6.
In this paragraph the procedure adopted for performed this test will be explained.
The first subject (Z.C.) was equipped with five sensors following the Measurement System Setup schematize in this table

Measurement System Setup 3		
Sensors	Sensors position	Fs [Hz]
438	Ski → 17,5 cm	75
442	Boot	75
436	Shank	75
439	Thigh	75
440	Sacrum	75

Fig 38: Sensor on the ski

Sensor 438

Fig 39: Sensor on the boot

Sensor 442

Fig 40:Sensor placed on subject

Each test was repeated in two Xsens configurations:

1. No reset
2. Alignment reset made on static standing

After this tests, the subject was invited to perform various skate skiing techniques in a short stretch of track, a "U" trajectory was followed, with a gentle downhill in the first part, followed by a 180 degrees rotation and finally the same length of track with, obviously, a gentle uphill.

Technique performed were:

a) Offset technique: to perform high force but low speed, used on steeper hills;
b) 1-Skate technique: used for accelerating and on moderate uphills;
c) 2-Skate technique: used at high speed on flats, gradual uphills and downhills.

Each techniques was repeated two times with different Xsens reset: the first trial was done without any reset, the second was performed by a static upright *Alignment Reset*; moreover granny and offset skate techniques were repeated changing the leg of thrust.

Fig 41: Subject trajectory

Fig 42: Sensors location

Fig 43: Static upright for Alignment Reset

Unfortunately, after this tests, sensors 438 and 442 (the two used on snowplough braking technique test) exausted their charge and the other two subject were sensorized with only 3 Xsens following this scheme:

Measurement system setup 5			
Sensors	Sensors position	Orientation reset	Fs[Hz]
436	Shank	No orientation	75
439	Thigh	No orientation	75
440	Sacrum	No orientation	75

The subject performed classic skiing technique on the same track of the first subject, roughly along the same trajectory. In the first time no reset was done to Xsens subsequently the *Alignment Reset* in the physiological standing position was performed.
The third subject executed the same tests as the second subject: for the last test, another type of Xsens reset was explored: when *Alignment Reset* is performed with wearing sensors, real posture of person is lost because this operation set a new coordinate frame for each sensors; for these reasons the *Alignment Reset Pack* was introduced.

The primary aims of the tests were: to assess the difference among three reset procedures, to understand which of these is more recommended for biomechanical applications, and to have a feedback regarding the MTws' behaviour when performing sports acts in several operative conditions. Considering the amount of data obtained during the tests, and the corresponding lengthy and complicated analysis, we will be report directly the results for brevity.

In subjects opinions the sensors did not interfere with motions, the straps were sufficiently fixed to avoid slippage, and, at the same time, did not limited the muscular normal activation.

The information about the physiological reference position are valuable data because they allow to know the initial subject/patient position (including the Xsens positioning error). For this reasons, because the *Object* and *Heading Reset* do not set all angles to zero, these two type of reset were classified not adapt for this applications. The same consideration can be done when the Earth coordinate system is taken as reference, and if the *Alignment Reset* is performed with the subject standing in the physiological reference position. In this last case, the first angles value returned are all zero and they don't give information about the subject/patient physiology or about MTws™ positioning but only about the relative motion of the segments from the physiological reference position. Considering this reset features, the *Alignment reset pack* should be the best for biomechanical applications, because it can give both technical and anatomical information having set the same coordinate system for all sensors.

4.2.4 Reset and angular velocity test

This paragraph will be recalled in chapter 6, where we will analyze the subjects' body calibration target: however this test was performed due to an incongruence highlighted during the previous pilot ski tests. This can be also classified as a preliminary test because it allowed understanding more features of MTws™. During data analysis of Cermis some inconsistencies were detected between the orientation data and the angular velocity data: the in fact latter were output with respect to axes differing from those used for the orientation data: therefore other tests were planned in laboratory in order to understand the reasons of these unexpected results. Aim of the tests was to clarity the different axes used for the orientation data and the angular velocity data.

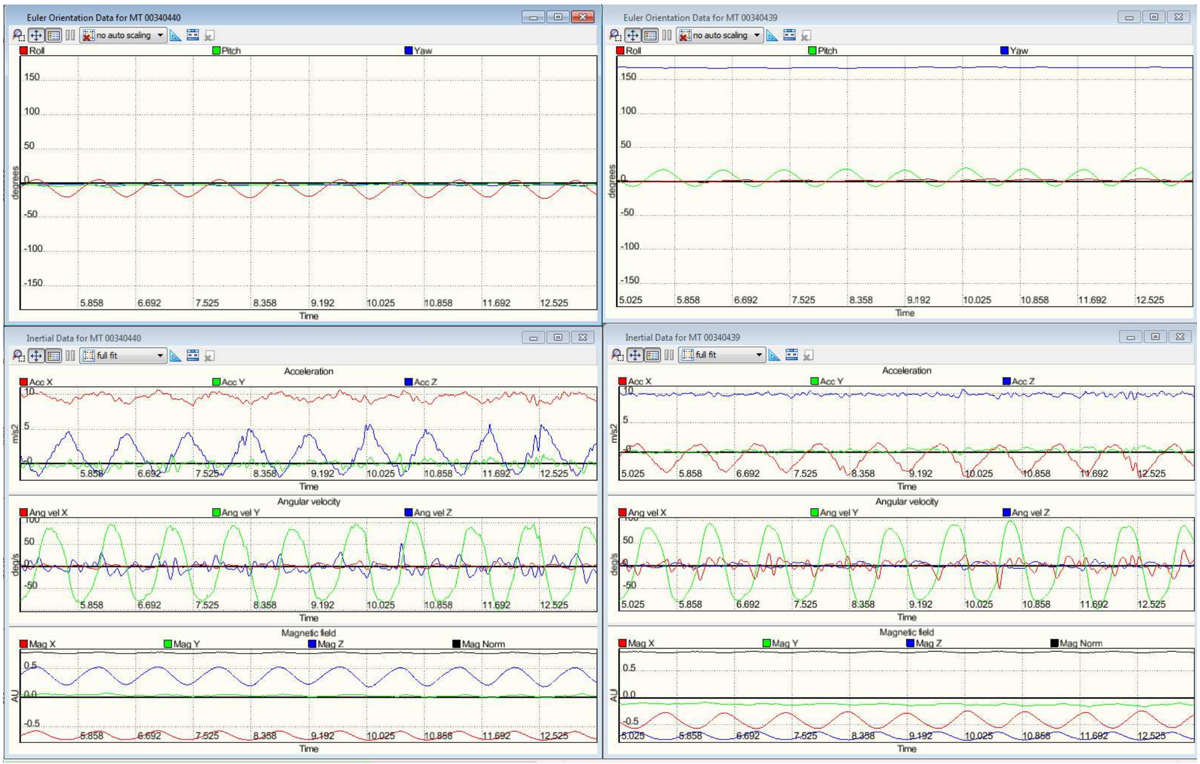
The first step of these tests consisted in simple movements around fixed axes, with the 436 MTw™ fixed on a totally non-ferromagnetic support. An *Alignment Reset* allowed to redefine the system coordinate frame and, after a validation of reset, three simple rotation around the coordinate system axes of the new coordinate system ***S'*** were performed.

Results suggested that the orientation data are calculated with respect to the reset coordinate frames', but there wasn't correspondence with the angular velocity data.

The second step of the test was carried out with two Xsens (440 and 439), both sensors were fixed at the same non-ferromagnetic support, performing the some movements. To the sensor 440 sensor the *Alignment Reset* was imposed to redefine its coordinate frame in this way:

- New Z' axis coincident with Z axis of sensor coordinate system ***S***;
- New X' axis opposite with Y axis of ***S***;
- New Y' axis coincident with X axis of ***S***.

Three rotations were conducted, like on the first step, to evaluate the difference between Xsens with one or the other reset. For example the following is a graph of X axis of the 440 sensor:



a) *b)*

Fig 44: Orientation (top) and inertial data. (a) Sensor 440 (b) Sensor 439

In this graph is possible to note that when the 439 sensor is moved about *Y* axis, the angular velocity data are correctly returned about *Y* axis (Pitch angles). Regarding the 440 sensor, the motions were related to the *X'* due to the *Alignment Reset*, but the angular velocity data are still related to the *Y* axis. Moreover, even it the *X'* axis was opposite to *Y* axis, the orientation follows a correct trend but the angular velocity data are the same of both sensors.

Other tests reported the same results with an *Object Reset*. The conclusion taken is as follows: the orientation data and the angular velocity data are related to the same coordinate frame once that the reset is performed. More precisely the orientation data are calculated with respect to the new coordinate frame ***S'*** for the sensor 440, to which an *Alignment Reset* was performed. However the angular velocity data are calculated with respect to the sensor coordinate frame ***S***.

This evidence is not corresponding to the Xsens User Manual, that reports "Once this *Alignment Reset* is conducted, both inertial (and magnetic) and orientation data will be output with respect to the new S' coordinate frame." [Pg. 54 for *Object Reset* and 55 for *Alignment Reset*].

However the angular velocity is defined as the rate of change of angular displacement and it is calculated like the first derivative of the angular values, so, if angular velocity data were calculated with respect to the new coordinate system ***S'***, and the orientation data about the *Y'* axis of the 440 sensor are nulls or constant, the angular velocity data about *Y'* axis should be null.

To bypass this incongruence, the angular velocity data are calculated by derivation from the orientation data in the Matlab software created to analyze data. This solution will be explained in details in Chapter 7.

4.2.5 Gait analysis test

The successive test was executed on May 3rd in the Biomechanics Laboratory at the DIM. The test's aims were: to perform motion capture sessions of gait analysis using both Xsens and optoelectronic systems for comparison in order to confirm if the *Alignment Reset* Pack is really the best solution for these applications.

The subject A. P. wore the markers and the MTws™ where placed in this mode:

1. Sensor 442 → Sacrum
2. Sensor 440 → Thigh
3. Sensor 439 → Shank

4. Sensor 438 → Right foot
5. Sensor 436 → Left foot

To obtain comparable results from both systems, it was fundamental that each marker forming the frame and the correspondent MTw™ would to the same movements. This consideration can be obtained with the three markers (needed for creating a reference frame) placed as closer as possible to the correspondent MTw™, and with a perfect coupling in order to transmit the same motion to both systems. It is evident that this solution is impossible, because markers must have a minimum distance between each other to be distinguished by the optoelectronic system. All of these reasons led to this solution: the body strip has a plastic clip to contain the MTw™ and under it there is a small slot. Two small aluminium supports with a "T" shape were created , the longer segment was inserted under the strip's plastic clip and, on the three ends, were placed the three markers (Figure 44).

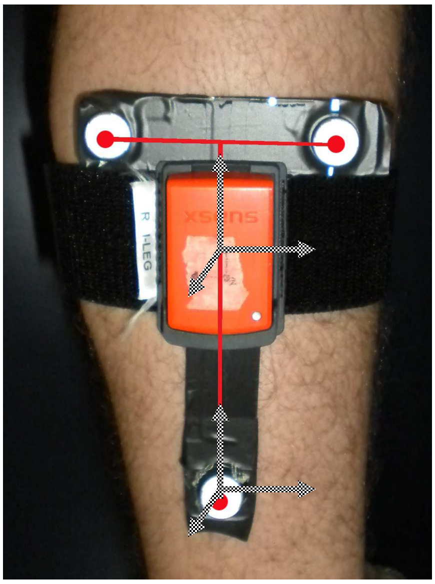


Fig 45: Embedded system obtained

By this way an embedded system was obtained and both MTw™ and optoelectronic systems recorded the same motions. Measures however aren't error-free because it can be a different alignment between MTw™ axes and axes reconstructed from markers, moreover Xsens Technologies said that it can be an error about 3° between real MTw™ position and its external box.

During this test, the two "T" structures were positioned under the strap of the sensors attached to the Thigh and the Shank. Moreover T shaped structures were covered by a dark tape to avoid reflects that could be revealed by video cameras. The three markers on the aluminium structure formed a so called “technical frame”, because it doesn’t gives directly anatomical data.

The *Alignment Reset Pack* was modified because, if sensors have the *X* axis pointing upwards during the operation of reset, when the *Alignment Reset* is performed, the system can’t uniquely identify direction and orientation of the new *X’* axis. Therefore, to decide direction and orientation of *X* axis, the pack of MTws™ must have an inclination which identify the direction that the new *X′* axis should take. To simplify the reset operation, a totally non-ferromagnetic horizontal surface was prepared on which the MTws™ were positioned during the reset. Using this device the reset pack is simpler and, it performed on an horizontal surface with orthogonal faces, allows to obtain the same coordinate system for all sensors. Moreover to choose the desired direction of new *X’* axis is sufficient to tilt the surface and to measure the angle formed with an inclinometer, called *Reset angle*. Knowing the Reset angle it is possible to take into account during the data analysis step, obtaining results which refer to the coordinate system that would be created performing the *Alignment Reset Pack* on a horizontal surface. Summarizing, the Alignment Reset Pack is performed on a horizontal surface tilted (in the direction chosen for the new X’ axis) of a known Reset angle thanks to the inclinometer. The Reset angle will be offset during the data analysis step, erasing totally the effect due to surface tilt. The Reset angle of this test was -5.7° about the Y’ axis.

In this test, the new sensor coordinate system ***S’*** imposed by the *Alignment Reset Pack* was:

- *X’* axis on gait direction as ab-adduction axis;
- *Z’* axis pointing upwards as intra-extra rotation axis;
- *Y’* following the right hand rule as flex-extension axis.
-

The BTS optoelectronic system has set the default coordinate system:

- *X* axis on gait direction as ab-adduction axis;
- *Y* axis pointing upwards as intra-extra rotation axis;
- *Z* axis following the right hand rule as flex-extension axis.

In this test, worthwhile underline that Xsens and BTS hadn’t the same reference coordinate system: the Xsens had the *Y’* axis as flex-extension axis instead the BTS system used the *Z* axis. The results in this chapter are exposed to present the difference obtained between the two system with these coordinate systems. The new method (exposed on Chapter 5) are developed to fix the discordance obtained in these tests.

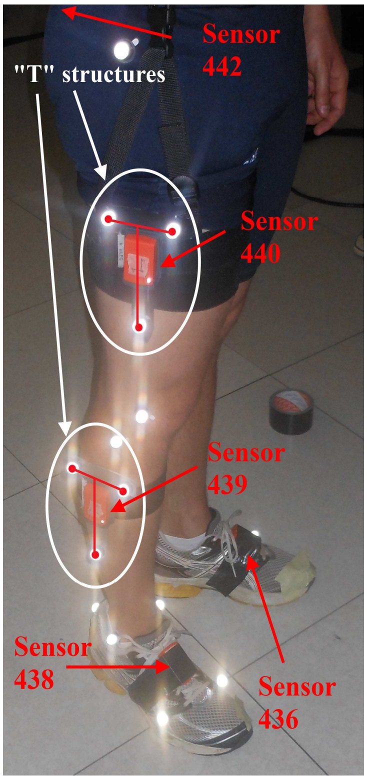


Fig 46: Sensor location

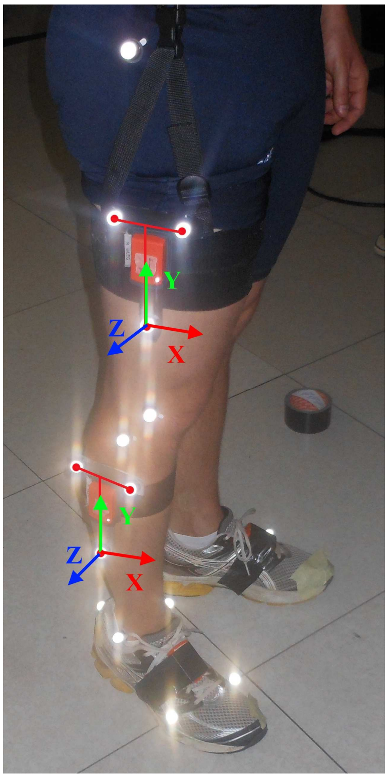


Fig 47: BTS coordinate systems

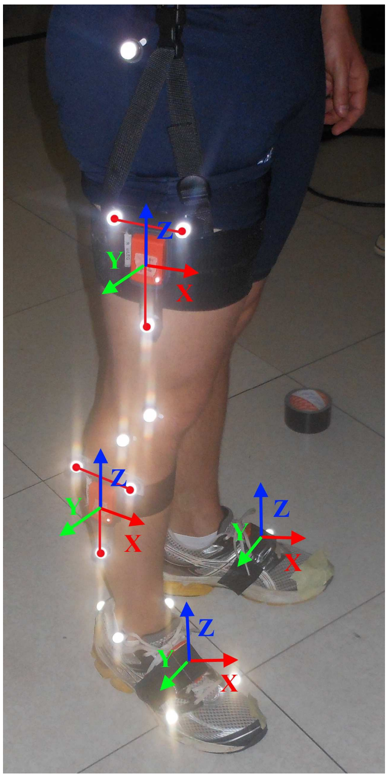


Fig 48: Xsens coordinate systems

However to compare the two systems, during the data analysis, the BTS coordinate system was modified to obtain the same reference frame for both systems.

The BTS optoelectronic system has been calibrated obtaining this calibration volume dimensions:

On X axis direction	3.85 [m]
On Y axis direction	1.98 [m]
On Z axis direction	1.65 [m]

Standard deviation	0.308
Mean	0.351

The subject was then asked to take a standing position (considered as the physiological reference position for gait analysis test) to record the *Static angles*. After this, the subject walked inside the calibrated volume to record the motions. Xsens *Segment angles* were compared to the BTS *Segment Angles* only for the sensors 439 and 440, the only two with the “T” structure.

Initially, the subject was invited to take the *physiological reference position* and the *Static angles* returned are:

	Sensor 436 (Left foot)	Sensor 438 (Right foot)	Sensor 439 (Shank)	Sensor 440 (Thigh)	Sensor 442 (Sacrum)
Roll (Φ) [°]	-8.5183	2.0316	1.9113	4.4413	-6.0252
Pitch (Θ) [°]	17.4454	19.7934	-8.4150	-8.5471	14.0497
Yaw (Ψ) [°]	8.6101	-23.4352	-4.1818	0.3331	-6.8127

The subject of this test was healthy with no orthopaedic functional limitations, therefore these *Static angles* give information only about the placement of MTws™ to the subject's body.

First set of analyzed data were the *Segment Angle*:

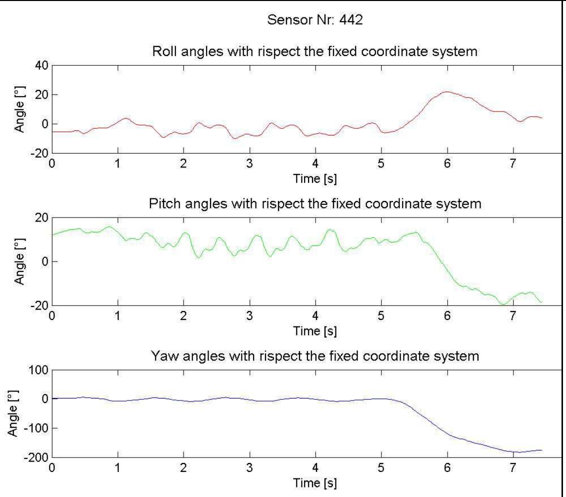


Fig 49: Sacrum movement(Segment angles)

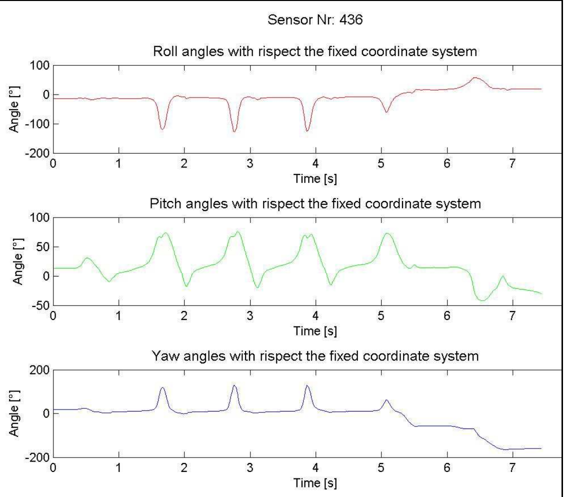


Fig 50:Left foot movement(Segment angles)

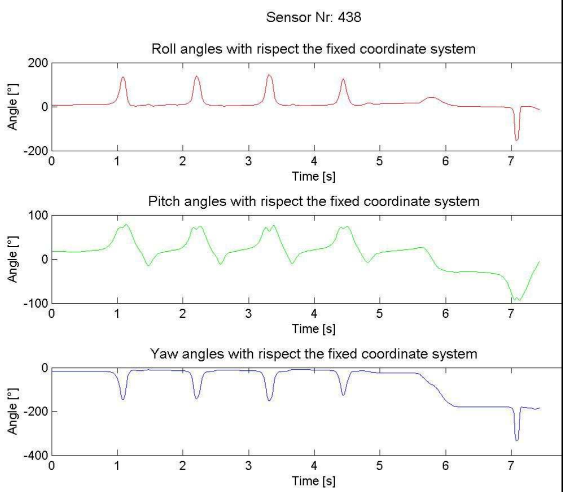


Fig 51: Right foot movement(Segment angles)

In the graph of the sensor 442 it can be observe the pelvis movements during walk, with ab-adduction and the flex-extension components due to the torsion of the trunk when a leg is carried forward. The graphs of the sensors 436 and 438 represent the movements of the right and left foot. In all of this graphs, between 5.8 and 6 seconds, the subject performed an inversion of direction of 180° anticlockwise. This motion is very visible on the Yaw angle.

The graph below shows the *Segment angles* comparison, calculated by the Cardan angle resolution:

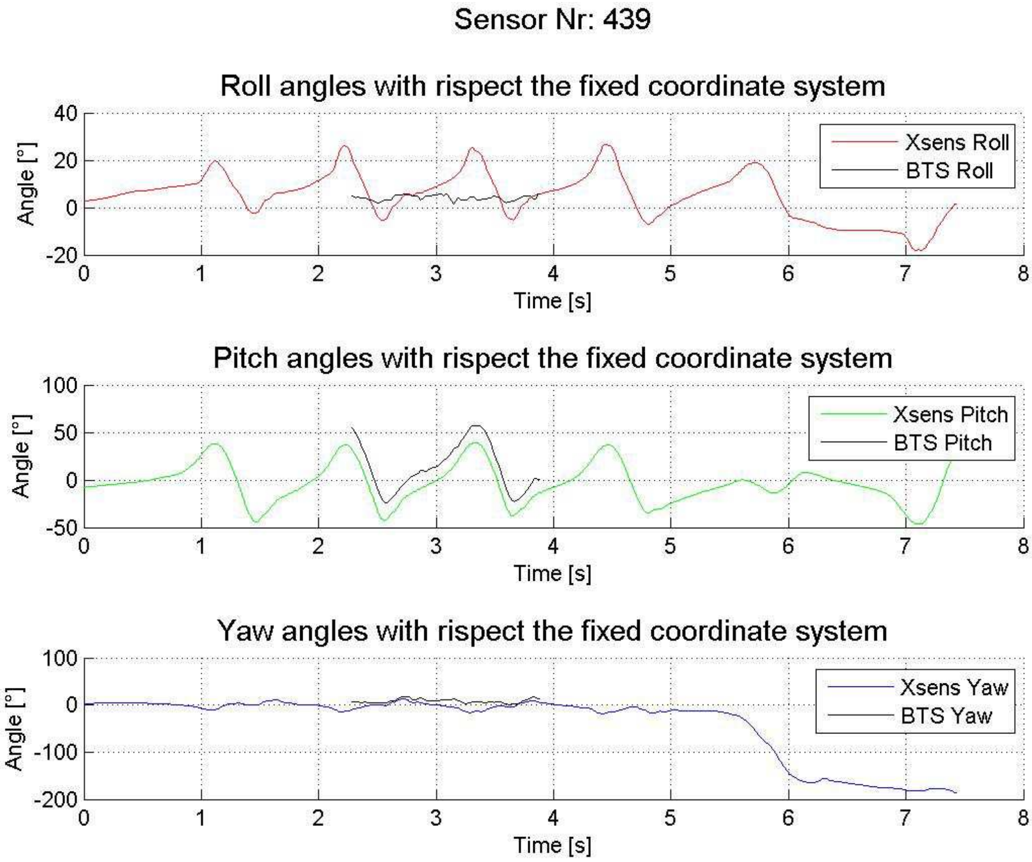


Fig 52: Shank Segment angles comparison

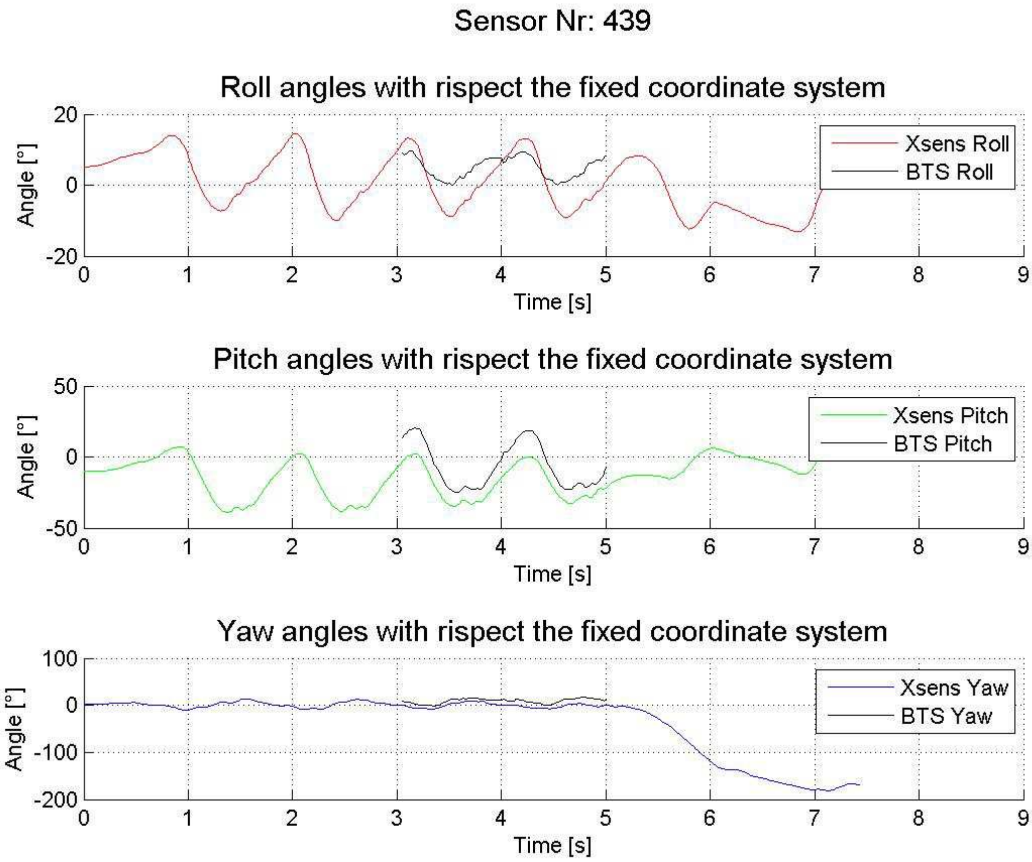


Fig 53: Thigh Segment angle comparison

In the previous graphs the differences between the *Segment angle* of the optoelectronic system and the *Segment angle* of Xsens system is presented, and these differences are amplified in the *Segment to Segment angles*, as is possible to note in the following graph:

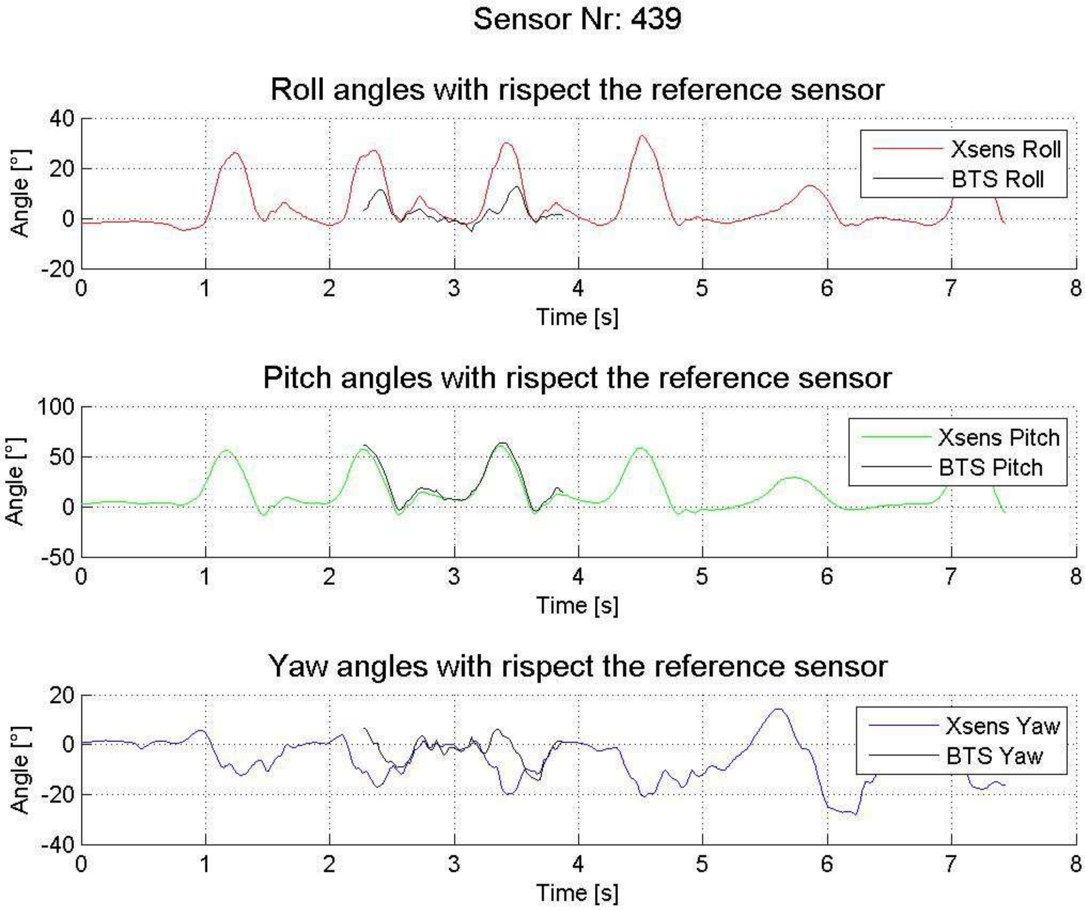


Fig 54: Knee Segment to Segment angles comparison

The ab-adduction angles are physiologically unlikely in a healthy subject, because there are peaks of 30° of the Shank with respect to the Thigh, however the two others motions results comparable between the two systems.

4.2.6 Treadmill test

After the gait analysis test, a treadmill test was performed with the same sensors and systems configurations as the previous test. A treadmill with four markers at the extremity was inserted in the calibration volume, and the subject was invited to run at two different speeds:

- 10 Km/h;
- 14 Km/h.

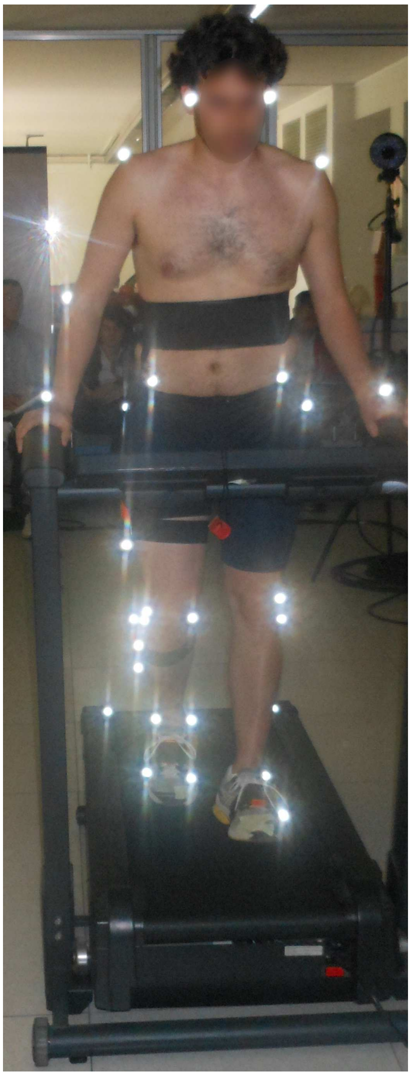


Fig 55: Subject during treadmill test

Following plots are presented side by side to compare the differences between the *Segment angles* during the treadmill test at 10 km/h and the *Segment angles* at 14 km/h:[5]

[5] Considering that the ab-adduction angles can't be physiologically correct.

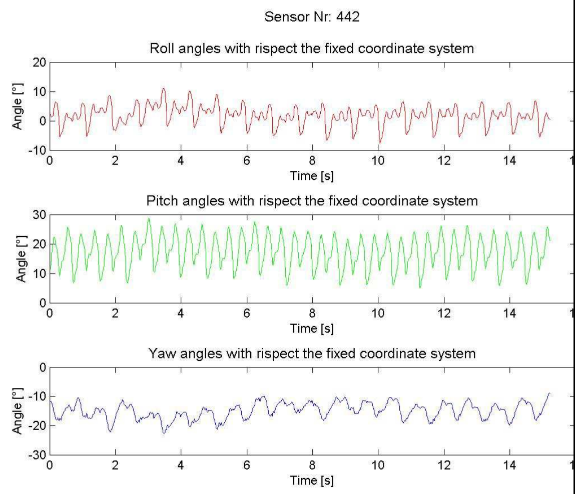
<table>
<tr><th>Run at 10 Km/h</th><th>Run at 14 Km/h</th></tr>
<tr><td>


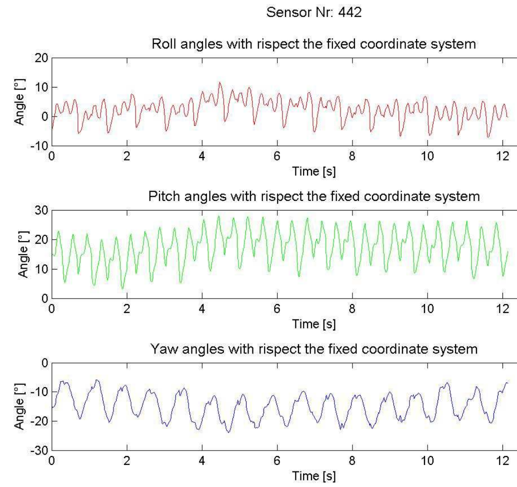
Fig 56: Sacrum movement (Segment angles)
</td><td>


Fig 57: Sacrum movement (Segment angles)
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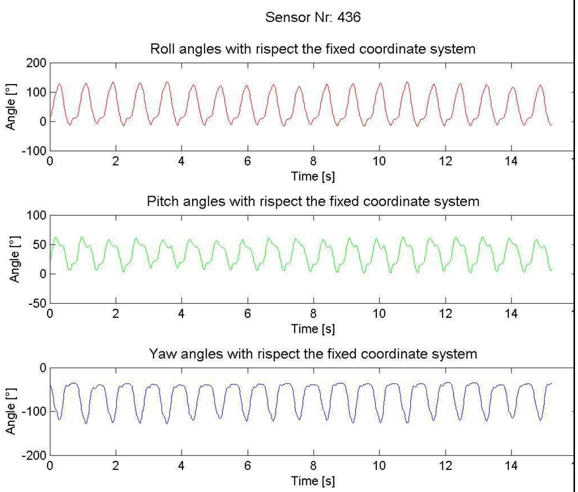

Fig 58: Left foot movement (Segment angles)
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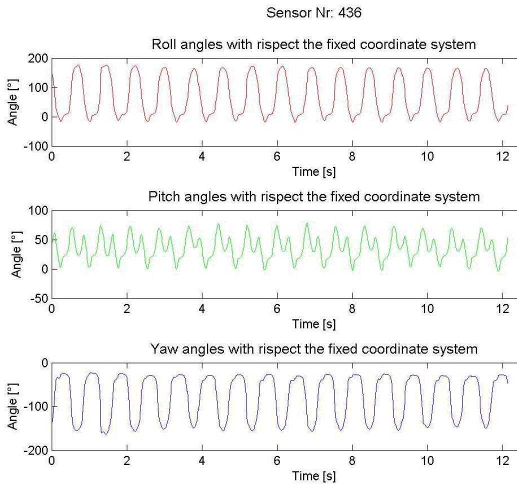

Fig 59: Left foot movement (Segment angles)
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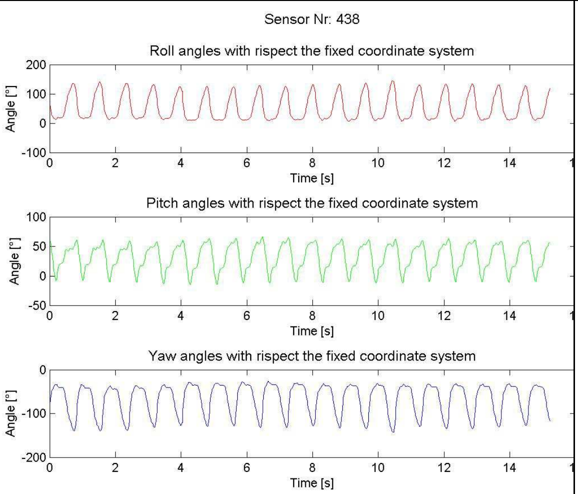

Fig 60: Right foot movement (Segment angles)
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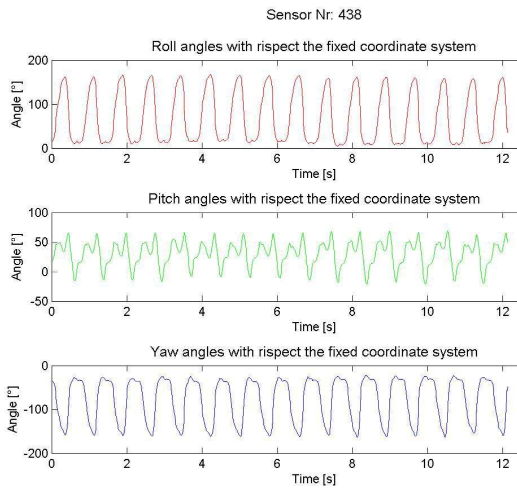

Fig 61: Right foot movement (Segment angles)
</td></tr>
</table>

In the figures 61,62,63 and 64 are shown the comparison of *Segment angles* and in figures 65 and 66 are presented the Shank to Thigh *Segment to Segment angles*. In each of next pages, the graph on top is referred to the 10 Km/h test and the other one to the 14 Km/h test.

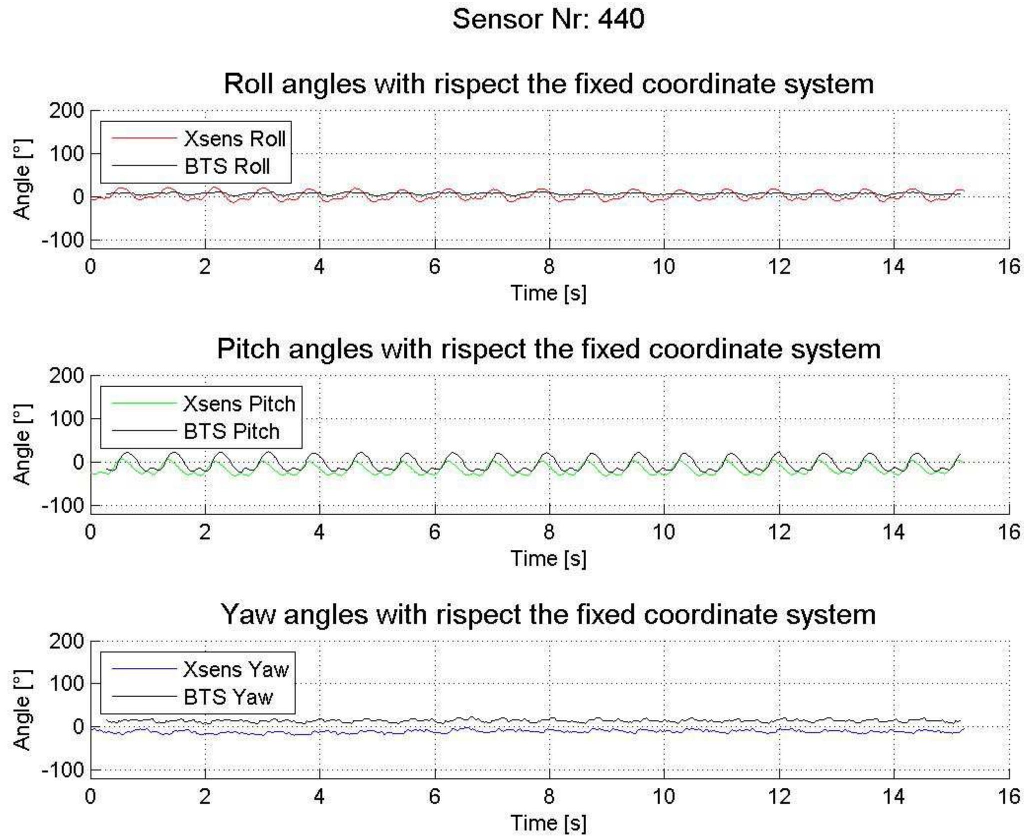

Fig 62: Thigh Segment angles comparison (10 km/h test)

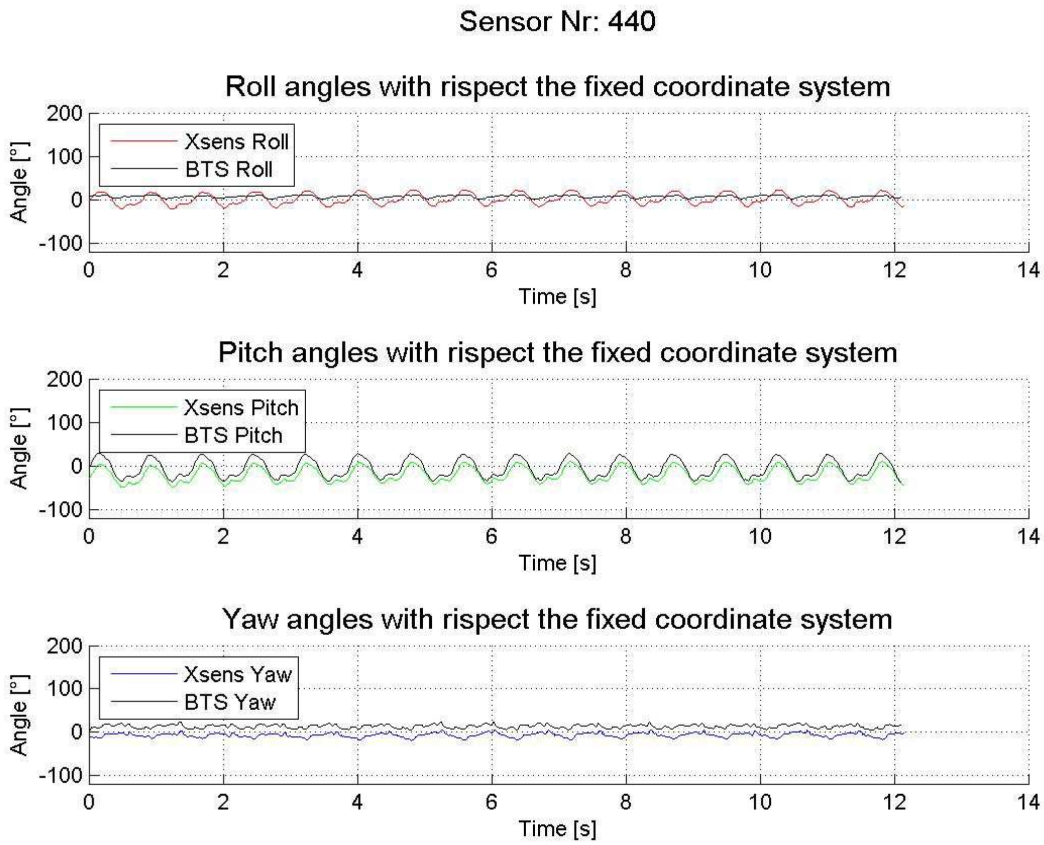

Fig 63: Thigh Segment angles comparison (14 km/h test)

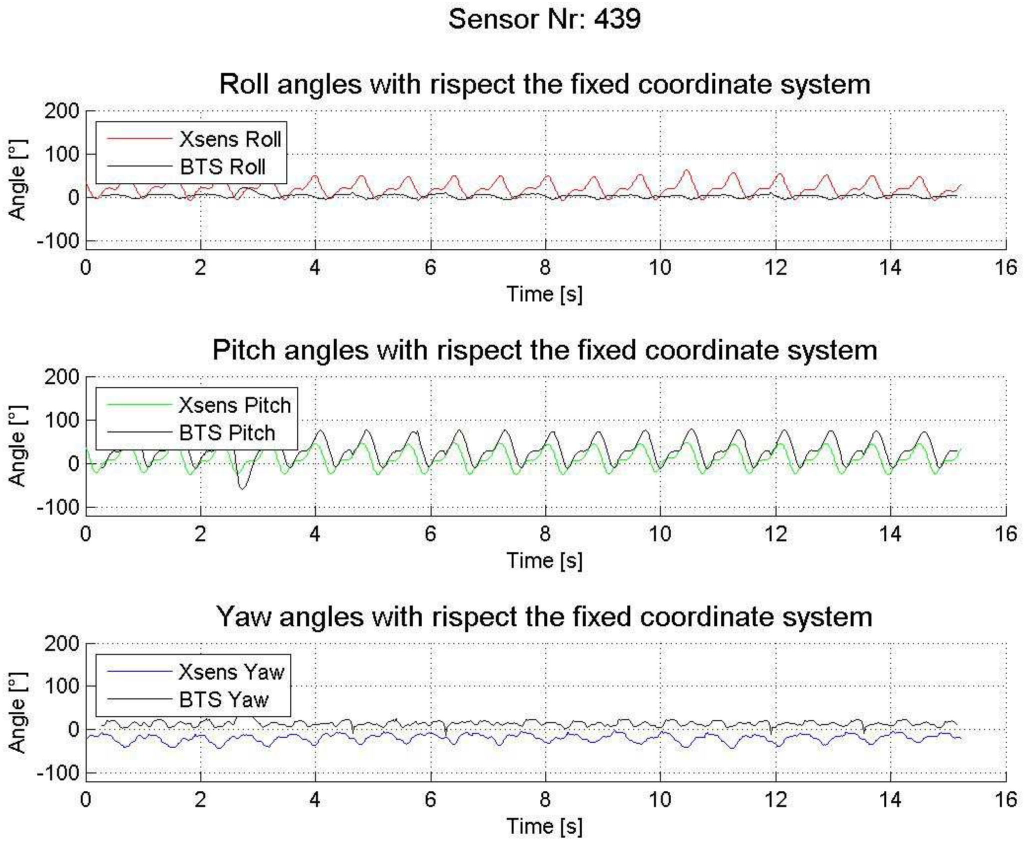

Fig 64: Shank Segment angles comparison (10 km/h test)

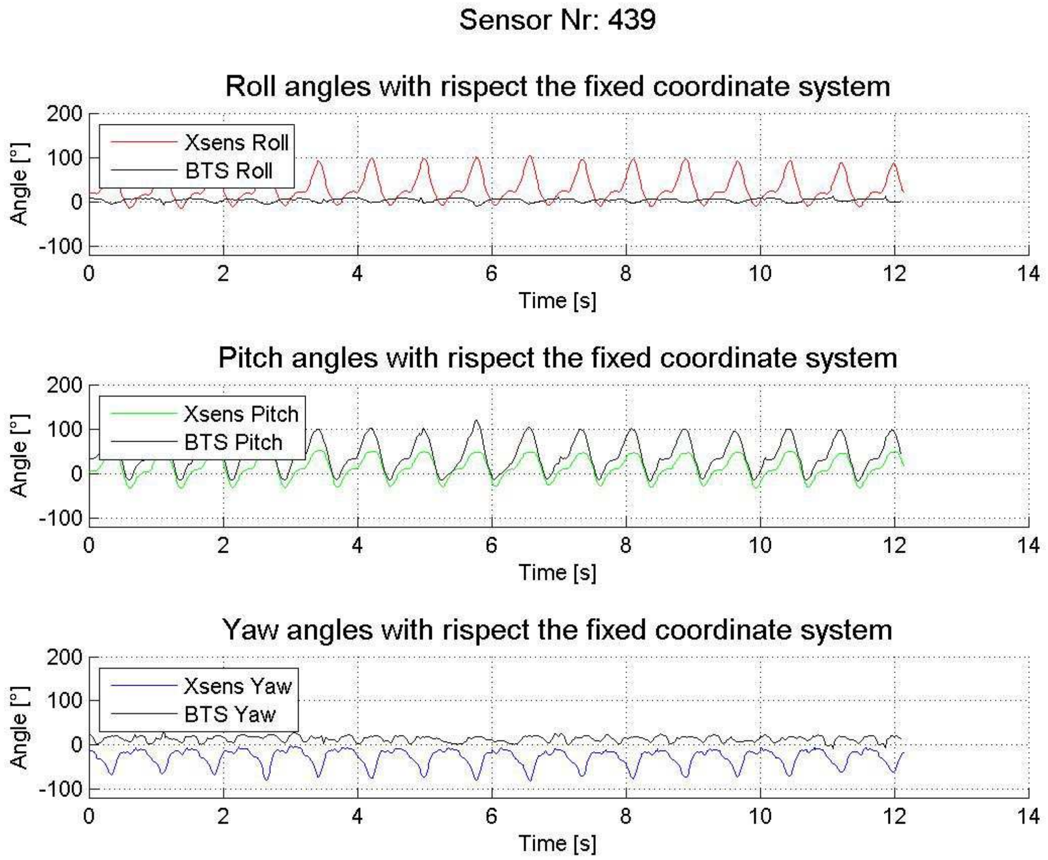

Fig 65: Shank Segment angles comparison (14 km/h test)

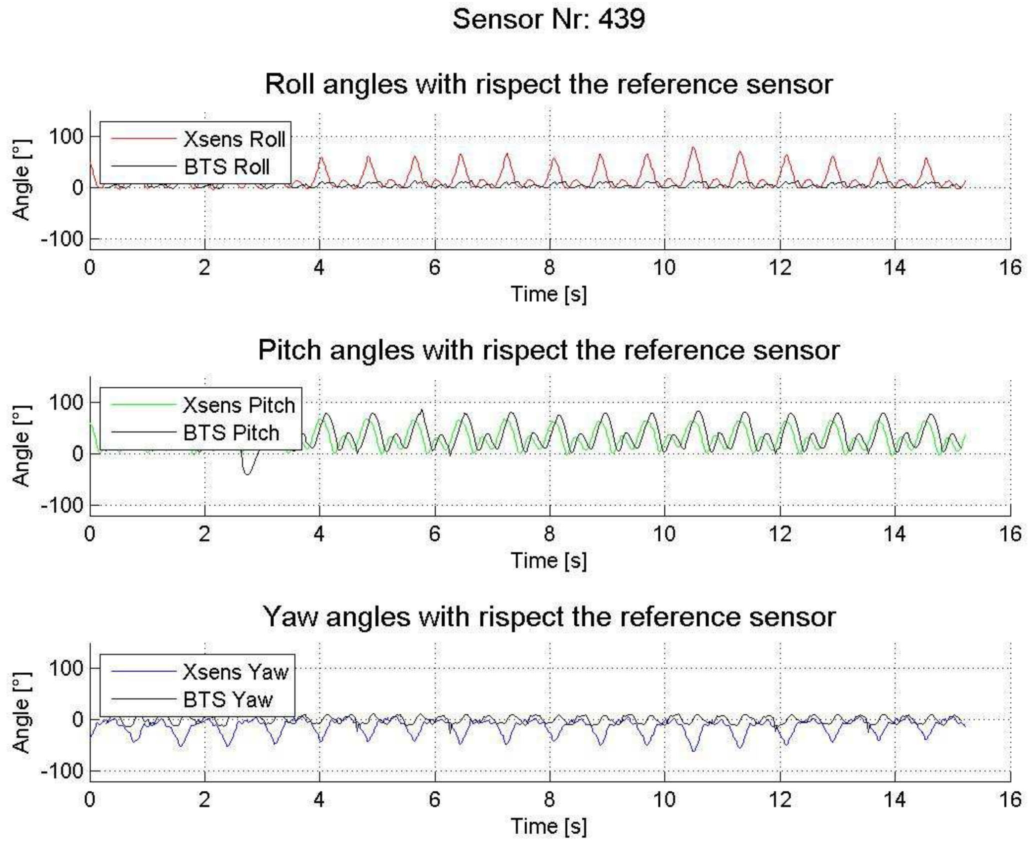

Fig 66: Shank to Thigh Segment to Segment angles comparison (10 km/h test)

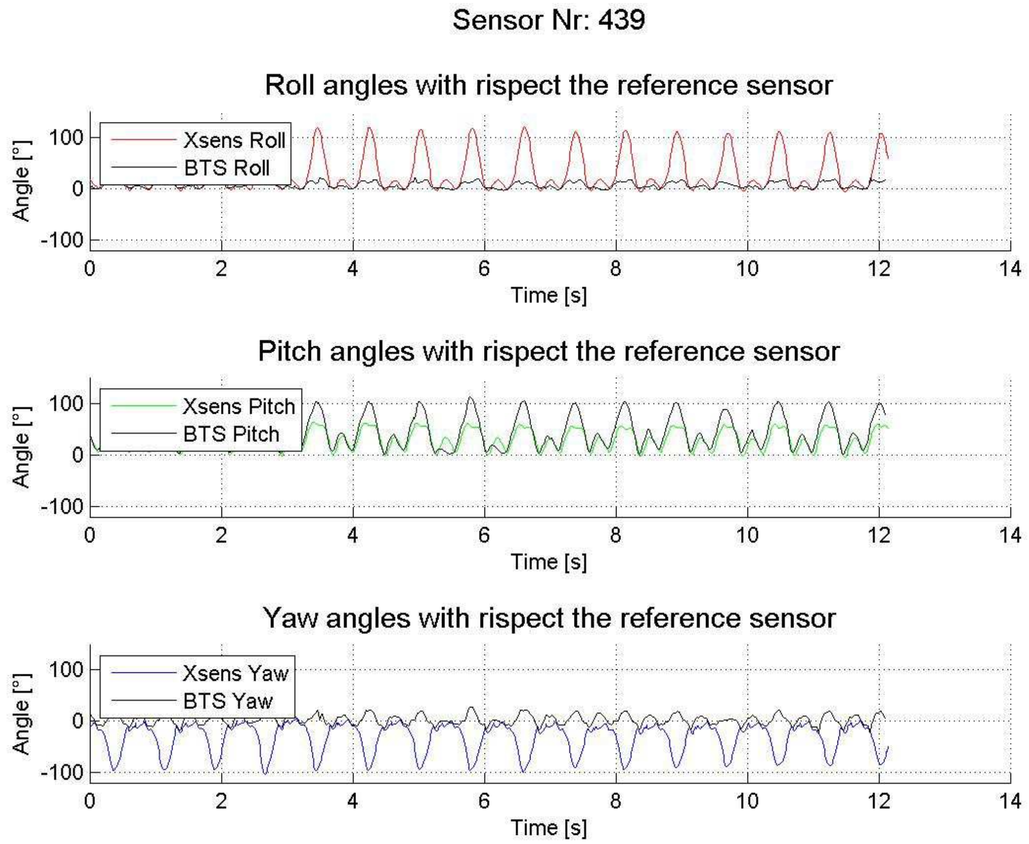

Fig 67: Shank to Thigh Segment to Segment angles comparison (14 km/h test)

In this test the big differences between Xsens and optoelectronic system regarding the two minor motion axes are evident, the axis with the larger movement are comparable. This test also shows that the matching is of inverse proportionality than the motions speed, on the other hand it is necessary to consider the higher possibility of artefacts, precisely due to motions speed.

4.2.7 Starting blocks test

This test was carried out after the treadmill test: due to the previous tests, the video cameras were moved and the BTS calibration was lost, so the optoelectronic data were not analyzed. To perform this test, starting blocks were fixed to the force plate, into the calibrated volume and a marker was dropped behind the subject as a start signal. By this way it was possible to calculate the time between the moment in which the marker touched the floor and the moment in which the subject started the motion. This is the reaction time of subject.

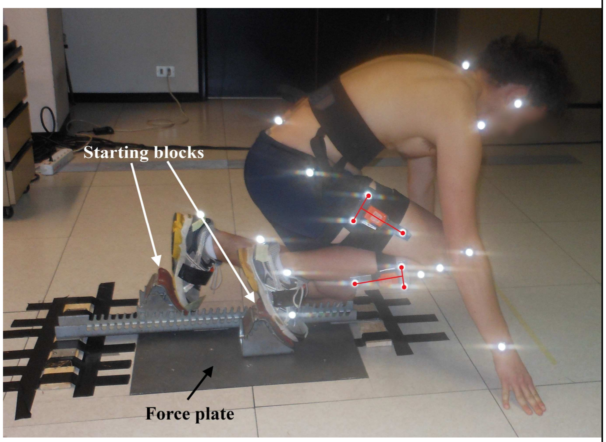

Fig 68: Starting block position

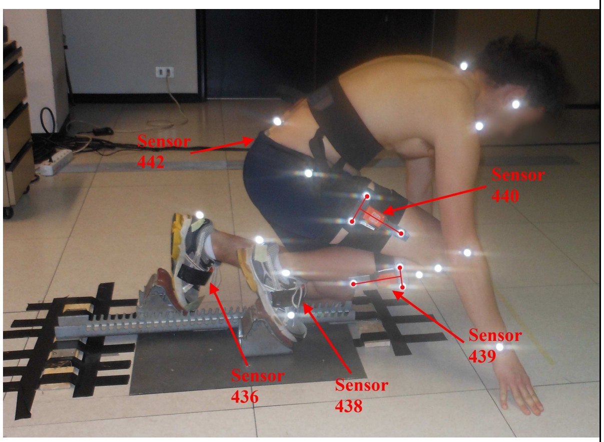

Fig 69: Sensor placement

In the test analyzed, the subject had had a reaction time of 0.183 sec, however, for all test made, the subject had always had a reaction time between 0.17 and 0.22 sec, which are typical values of a healthy subject.

For the *Segment angles*, the most significant is the sensor 442, because recorded angles that allow to reconstruct the position of subject on the starting blocks:

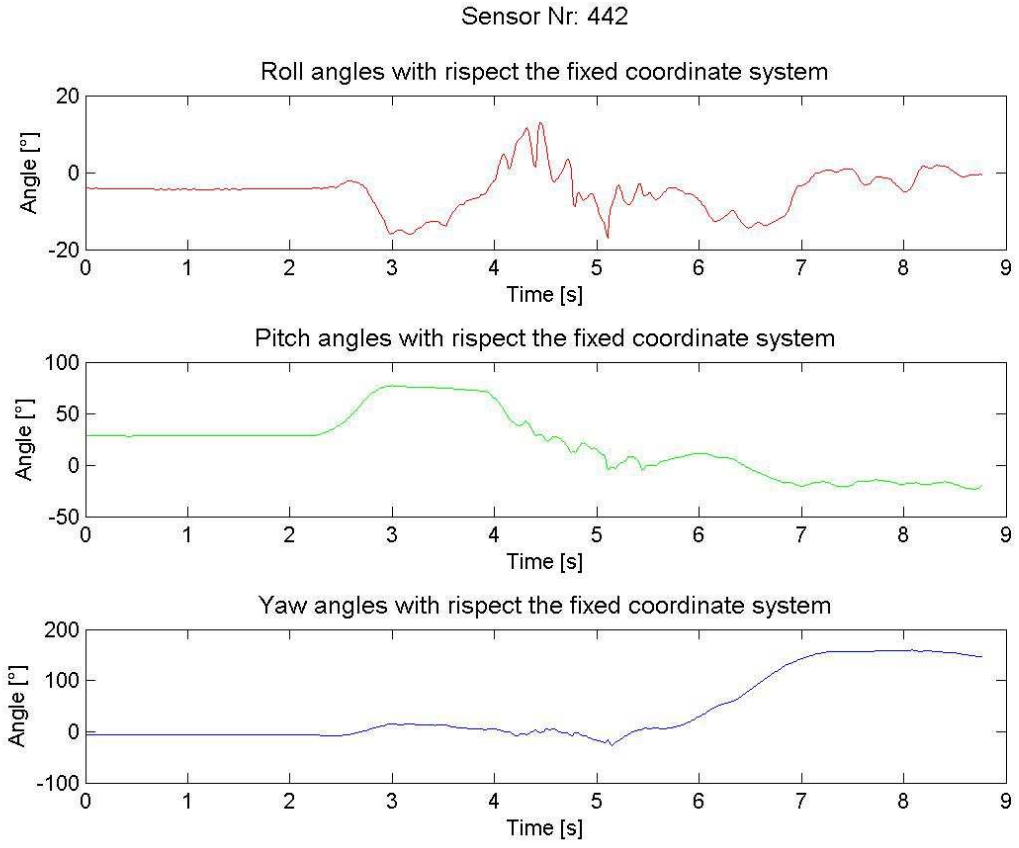

Fig 70: Sacrum movement (Segment angles)

Following the Y (Pitch) axis trend, the subject was in the position shown on the Fig. 65, up to 2.2 seconds, and the sensor noted an angle with respect to the physiological reference position of about 28.5°.Then, in the position before the start, this angle increased up to about 75°.

When the subject started, the posture changed to become a standing position, and the angles detected decreased to 0°. However, it must be considered that the sensor 442 was attached to the subject with tape (due to the other markers present on the iliac spines) and it could have moved due to rider’s power, adding artefacts to the signal.

The *Segment to Segment angles* between Shank and Thigh are show in Fig 67:

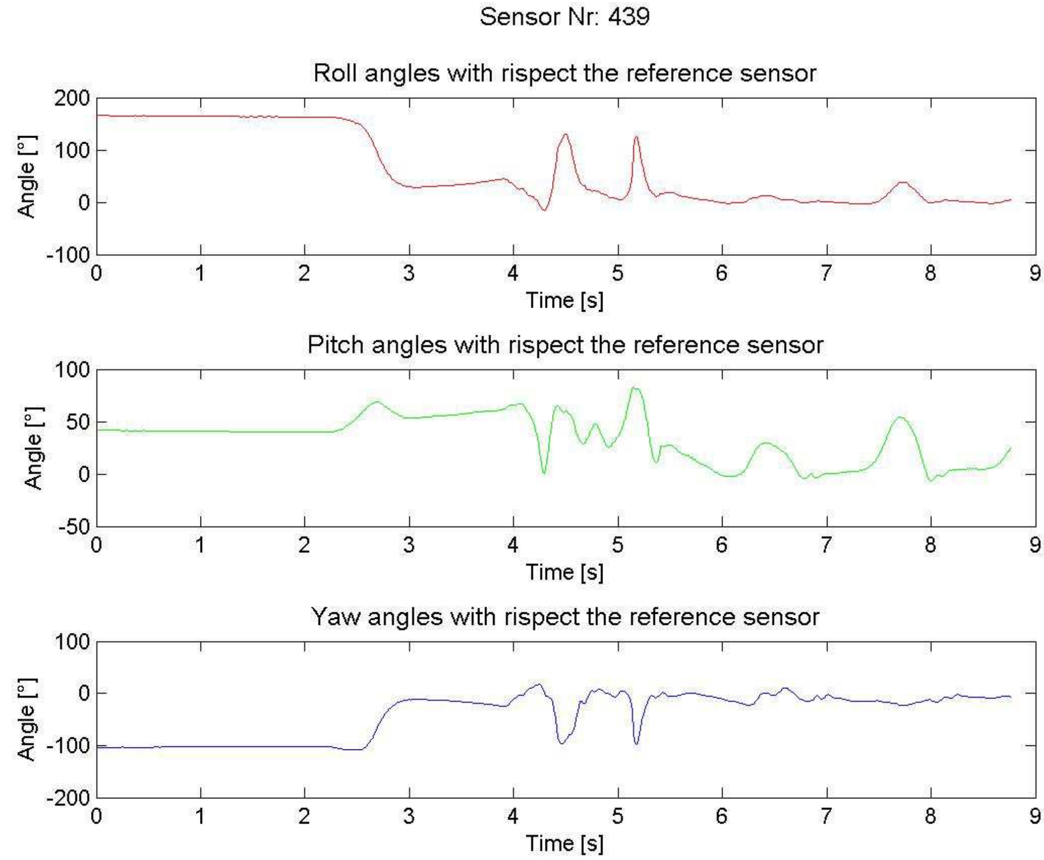

Fig 71: Shank to Thigh Segment to Segment angles

You can see in this chart the speed of movements which allow to extend the leg (Pitch angles became about 0° with respect to the *physiological reference position*) and the start of the gate (about 5 sec. identified by the Pitch graph). Moreover the flex-extension angles around 2.7 sec should be larger than the 48 degrees returned. This incongruence can be due to the compression of the calf on the Thigh.

4.3 Considerations about the preliminary tests

These tests allowed to understand the problems of the MTws and the necessary improvements for an efficient method to perform MoCap sessions and motion analysis with the MTw. They highlighted important differences about the angles of the two smaller motion axes (in gait analysis the ab-adduction and intra-extra rotation). These differences were due to the sequence of basic rotation matrices: indeed for all of these tests was set (by the *Alignment reset pack*) the frame suggested by the ISB which have X axis in the motion direction, Y axis pointing upwards and Z axis following the right hand rule, as sensor coordinate system. Using these sensor coordinate systems, the Xsens performed a different rotation matrices sequence to the optoelectronic system, therefore the final rotation matrices returned from the two systems were not equal, and, inevitably, the angles calculated were not the same. The method found to obtain the same angles between the two systems is explained in the following chapter.

CHAPTER 5

Validation tests

5.1 Reset method

A final method for using the MTws™ reset is found. It is the *Alignment Reset Pack*, which is performed with the horizontal device described in the previous chapter. The first step is to identify the desired coordinate system and, after, MTws™ must be properly positioned for the reset. To obtain the same new sensor coordinate system, the position on the subject's body where MTw™ should shall be evaluated. So, following how the Alignment Reset works, the correct reset position for each MTw™ can be found.

As explained in the 4.2.5 paragraph, applying the reset in the horizontal tilted device, it is possible to choose the direction of the X axis and, using an inclinometer, it's possible to measure the reset angle. Regarding the analysis data step, a particular "physiological rotation sequence" is required: first, the axis around which larger movement is performed, second, the axis around which intermediate movement is performed, third, the remaining axis. Every MTw™ returns the Euler "aerospace" angles measured by a fixed rotation axis $R_{XYZ} = R_Z R_Y R_X$ (as explained in the 2.4 paragraph).

To perform the correct rotation sequence as defined "physiological rotation sequence", there are two possibilities:

1. Modify the rotation sequence;
2. Set the axes to perform the right sequence.

The first point can't be applied because the Xsens executes a default *X-Y-Z* sequence, indeed the output modes are: quaternion, Euler "aerospace" angles or rotation matrix terms.

The second approach can obtained by performing the *Alignment Reset Pack* as explained in the previous chapter. If the reset is performed with the horizontal device tilted in the larger motion's direction, the *X* axis will have this direction and orientation, the *Z* axis will point upward and the *Y* axis will be oriented according to the right hand rule.

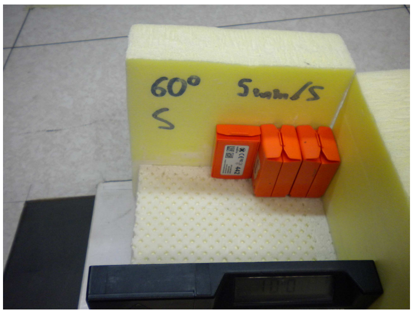

Fig 72: Alignment Reset pack

This approach use the reset to set the sensor coordinate system, in the way that the Xsens sequence rotation becomes equal to the "physiological sequence rotations".

This method is fundamental for the comparison between Xsens and optoelectronic system and its features will be explained in details in the successive paragraph.

5.2 Comparison between Xsens and optoelectronic system

The software of BTS optoelectronic system provides the users with multiple options for data analysis, including the ability of creating the coordinate systems and the ability to rotate the default laboratory reference system. When the reset is conducted following the method above mentioned, Xsens and optoelectronic system further have different reference coordinate system, but, using BTS software, it's possible to change the BTS coordinate system to obtain the same reference frame for both systems.

Once the same reference coordinate system and the same sensor/marker coordinate frame are obtained for both systems, the Xsens return angles calculated according to the Euler "aerospace" approach (XYZ sequence), whereas the BTS system return angles in according to the Cardan representation. The different approach to calculate angles doesn't affect the determination of the final position of the coordinate system, because it must be the same, but the intermediate rotations are different. Indeed the angles returned are different, because Xsens performs rotations about fixed axes, whereas the BTS performs rotation around moving axes. According to theory, when both systems refer to the same reference coordinate system performing the same movements and the same sequence of rotations the resulting rotation matrices must be equal. During the tests, the reference frame are modified to be the same for both systems and the rotation must be:

- $R_{Xy'z''} = R_X(\varphi)R_{y'}(\theta)R_{z''}(\psi)$ for the Cardan angles of the BTS system;
- $R_{XYZ} = R_z(\Psi)R_Y(\Theta)R_X(\Phi)$ for the Euler "aerospace" angles of Xsens.

Numerically, the two rotation matrices are equal, therefore applying the resolutive formulas of Cardan angles to the matrix obtained from Xsens, the angles in the Cardan representation are obtained:

$$R_{Xy'z''} = R_X(\varphi)R_{y'}(\theta)R_{z''}(\psi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\varphi & -\sin\varphi \\ 0 & \sin\varphi & \cos\varphi \end{bmatrix} \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} \cos\theta\cos\psi & -\cos\theta\sin\psi & \sin\theta \\ \cos\varphi\sin\psi + \cos\psi\sin\varphi\sin\theta & \cos\varphi\cos\psi - \sin\varphi\sin\theta\sin\psi & -\cos\theta\sin\varphi \\ \sin\varphi\sin\psi - \cos\varphi\cos\psi\sin\theta & \cos\psi\sin\varphi + \cos\varphi\sin\theta\sin\psi & \cos\varphi\cos\theta \end{bmatrix}$$

The angles ϕ,φ and ψ can be obtained with following formulas:

$\varphi = -\arctan\left(\frac{R_{23}}{R_{33}}\right)$	$\theta = \arcsin(R_{13})$	$\psi = -\arctan\left(\frac{R_{12}}{R_{11}}\right)$

On the contrary the following formulas will be applied to the Xsens rotation matrix:

$$R_{XYZ} = R_Z(\Psi)R_Y(\Theta)R_X(\Phi) =$$

$$= \begin{bmatrix} \cos\Psi\cos\Theta & -\sin\Psi\cos\Phi + \cos\Psi\sin\Theta\sin\Phi & \sin\Psi\sin\Phi + \cos\Psi\sin\Theta\cos\Phi \\ \sin\Psi\cos\Theta & \cos\Psi\cos\Phi + \sin\Psi\sin\Theta\sin\Phi & -\cos\Psi\sin\Phi + \sin\Psi\sin\Theta\cos\Phi \\ -\sin\Theta & \cos\Theta\sin\Phi & \cos\Theta\cos\Phi \end{bmatrix}$$

With this method it's possible to perform a comparison between the two systems and angles returned are theoretically the same.

Using the terms of the rotation matrices it's possible to calculate the *Segment to Segment angles* using the properties of the rotation matrix: each MTw™ returns the *Segment angles* which are calculated from the rotation matrix with respect to the fixed coordinate frame: $R_{S_n}^F$.

Having the matrices of each sensors, it's possible to calculate the rotation matrix with respect to another sensor coordinate system, e.g. a sensor placed on the Shank of a subject and a second sensor placed on the Thigh of the same subject, using the composition of rotation matrices it is possible to change the reference system and to calculate the angles between them, defining one sensor coordinate system like the reference coordinate system. The angles obtained with this method are called *Segment to Segment angles*:

$R_S^T = \left(R_T^F\right)^T R_S^F$	$R_T^S = \left(R_S^F\right)^T R_T^F$
This is the rotation matrix which transform the coordinate system of the Shank sensor with respect to the coordinate frame of the Thigh sensor. The angles returned will be:	This is the rotation matrix which transform the coordinate system of the Thigh sensor with respect to the coordinate frame of the Shank sensor. The angles returned will be:
Φ_{TS}, θ_{TS}, Ψ_{TS} or ϕ_{TS}, φ_{TS}, ψ_{TS}	Φ_{ST}, θ_{ST}, Ψ_{ST} or ϕ_{ST}, φ_{ST}, ψ_{ST}

5.3 Matlab software to perform comparison

To perform the analysis data step was developed a Matlab software which is composed by these functions:

- *Import data function:* imports the data returned from the MTws™, which are exported on *.txt* file using the MT Manager software. All data imported are saved in a *.mat* files which will be automatically loaded by the successive functions which elaborate of data. Thus the data importation step is performed only for the first time, with lower computational load to the elaboration data functions. In this program data are exported in the matrix rotation terms mode because, applying the property of rotation matrix (as explained in the 2.1.3 paragraph) it's possible to calculate, in addition to the *Segment angles*, the *Segment to Segment angles* (as defined in the 3.4 paragraph);
- *Matrices rotation sequences function:* allows to choose what is the resolution to be applied to the $R_{XYZ} = R_Z(\Psi)R_Y(\Theta)R_X(\Phi)$ or the $R_{Xy'z''} = R_X(\varphi)R_{y'}(\theta)R_{z''}(\psi)$ final matrix ;
- The *Reset angle function:* asks to the user if a Reset angle was used and, this angles can be erased from data of the correspondent axis;
- *Elaboration data functions:* execute the data elaboration. The matrix's terms are inserted in a cell structure, but the matrix is not reconstructed on variables because the computational load would be too high. Formulas explained in the previous chapters are used to calculate the *Segment angles*, required terms are contained in cells.

  The software automatically performs a data monitoring, erasing the Not-a-Number forms and fixing the problem of clipping data due to the mathematical singularity of both Euler "aerospace" and Cardan angles types.

  The Segment angles are shown for each sensor in Roll, Pitch and Yaw representation. The software also allows to calculate the *Segment to Segment angles* using the rotation matrix property explained in the previous chapter. The first sensor inserted on the import data function, is taken as the reference sensor and, even for these angles a data monitoring is performed. For all sensors inserted (excluding the reference sensor) the *Segment to Segment angles* are calculated;

- *Physiological reference position function:* allows to calculate the *Static angles* and the user can decide whether to delete these angles for the subsequent processing;
- *Gait analysis comparison function:* executes the comparison between Segment angles or/and Segment to Segment angles given from BTS optoelectronic system and Xsens systems. In this function an algorithm that synchronizes data (because during the tests there wasn't a trigger signal to set the same time of start) it's implemented. This algorithm calculates the range of time in which the optoelectronic system has recorded the gait and it finds the maximum value. Moreover it is calculated the maximum peak of Xsens data in the same range of time of the optoelectronic and the graph is synchronized on the maximum value of the larger motions axis. This algorithm performs the comparison both for *Segment angles* and *Segment to Segment angles*;
- *Graphs save function:* creates a folder in the original data's folder for every types of angles calculated and, in it, the software automatically saves all sensors' angles graphs.

5.4 Validation tests

These tests were performed to validate the method previously exposed and to perform comparison between BTS optoelectronic system and Xsens system.

5.4.1 Electrogoniometer test

In this test an electrogoniometer was used only as structure to execute the test. This device was chosen because it's formed by two stems joined by a pivot, so it allows only one degree of freedom. To place the sensors, it was traced the medial axis of each stems and both Xsens and markers was placed in these positions:

1. "Fixed" marker on the joint
2. "Moving" marker on the superior stem's medial axis
3. "Tip fixed" marker on the inferior stem's medial axis

1. Xsens 440 on the superior stem's medial axis
2. Xsens 442 on the inferior stem's medial axis

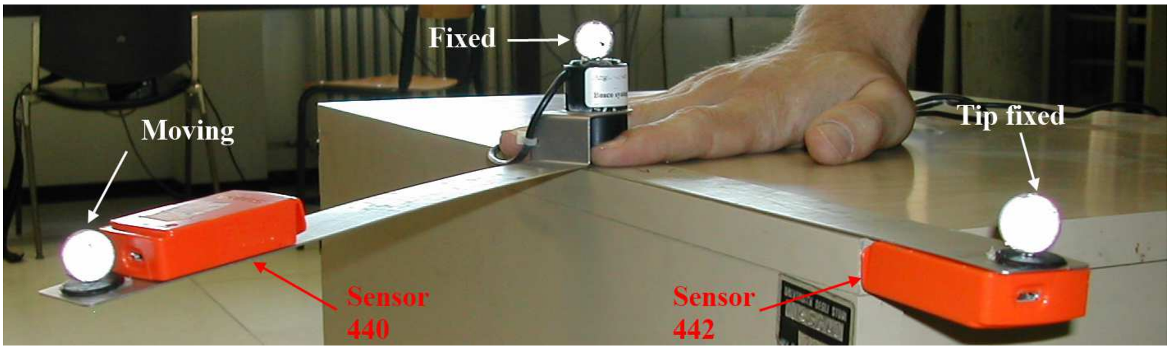

Fig 73: MTws™ and markers placement

Markers and Xsens were fixed on the stems medial axes with a perfect alignment between them.

The electrogoniometer with markers and Xsens was placed on an horizontal surface (89.9° measured with an inclinometer) and both Xsens were reset with an Alignment Reset. This reset was required to set the Z axis perfectly orthogonal to the surface (the orthogonality is always influenced by the accuracy of the MTws™).

Each movement was done with the electrogoniometer placed on the horizontal surface. Initially, preliminary tests were done to find the best method to perform the tests and it was decided to use the following procedure:

- The acquisition starts when markers and Xsens are aligned
- The first movement is to open the electrogoniometer by a small angle, because when it is in alignment configuration, the optoelectronic system doesn't recognize two markers on the tips (one on the superior and the other on the inferior one);
- The second movement is to open by a casual angle (both tests was performed) and this position is maintained for a few seconds (to recognize this phase during the analysis data step);
- The third movement is to open by a ~180° angle (the edge of the horizontal surface is taken as a reference) and this position is maintained for a few seconds;
- The fourth movement is similar to the second but in opposite direction;
- The last movement returns the electrogoniometer in alignment configuration.

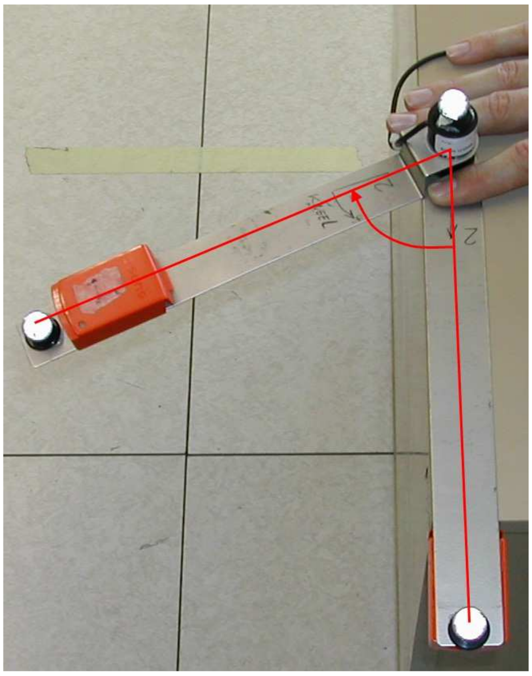

Fig 74: Example of a motion

The graph below represents the angles obtained during this test:

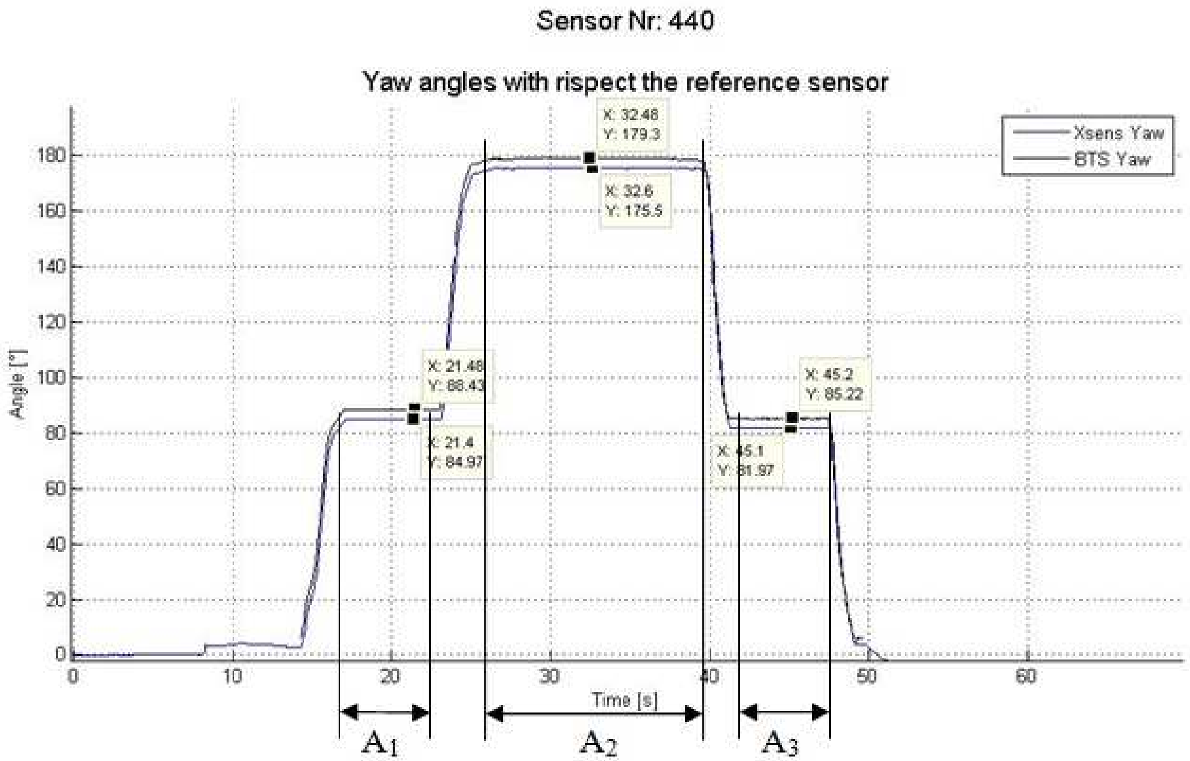

Fig 75: Segment angle of the electrogoniometer test

The angles are absolutely comparable to each other, however, in this test, the angles returned from optoelectronic system are always larger than the Xsens angles. Differences recognized are:

A_1	A_2	A_3
3.25°	3.46°	3.8°

This test was repeated with comparable results, therefore an angle included between |3° ÷ 4°| could be taken as the error between the BTS optoelectronic system and the Xsens MTws™ system.

5.4.2 2nd gait analysis test

The gait analysis test was a further validation test performed and it was executed following the method explained previously. The subject was dressed with 5 MTws™ arranged in the following way:

- Sensor 436 on left Shank;
- Sensor 438 on right Shank;
- Sensor 439 on right Thigh;
- Sensor 440 on left Thigh;
- Sensor 442 on sacrum.

One of the two "T" structures was placed on the right leg to create the marker's technical frame (as presented in the 4.2.5 paragraph).

The optoelectronic calibration system had reported this volume features:

On X axis direction	2.97 [m]
On Y axis direction	2.09 [m]
On Z axis direction	4.40 [m]

Standard deviation	0.297
Mean	0.345

The *Alignment Reset Pack* was performed with 10° of *Reset angle* around the *Y* axis, and it had set this coordinate system:

- X axis as the Flex-Extension axis;
- Y axis as the Ab-Adduction axis;
- Z axis as the Intra-Extra rotation axis.

Initially, the subject was invited to take the *physiological reference position* and the *Static angles* returned are:

	Sensor 436 (Left Shank)	**Sensor 438 (Right Shank)**	**Sensor 439 (Right Thigh)**	**Sensor 440 (Left Thigh)**	**Sensor 442 (Sacrum)**
Roll (Φ) [°]	-4.3940	-5.7050	-5.7000	-7.1091	-5.7690
Pitch (Θ) [°]	-6.7397	7.8326	7.3349	-9.6506	-1.5315
Yaw (Ψ) [°]	-13.6629	6.5644	-3.9286	12.6196	7.6297

The subject of this test is healthy with no orthopaedic functional limitations, therefore these *Static angles* give information only about the placement of MTws™ on the subject's body.

The subject walked for 3 times in the calibrated volume while both systems were recording the motions. The comparison between the two systems was performed only for the 438 and 439 sensors, because "T" structure with markers were placed only behind these sensors.

First data analyzed were the *Segment Angle* of the first gait test:

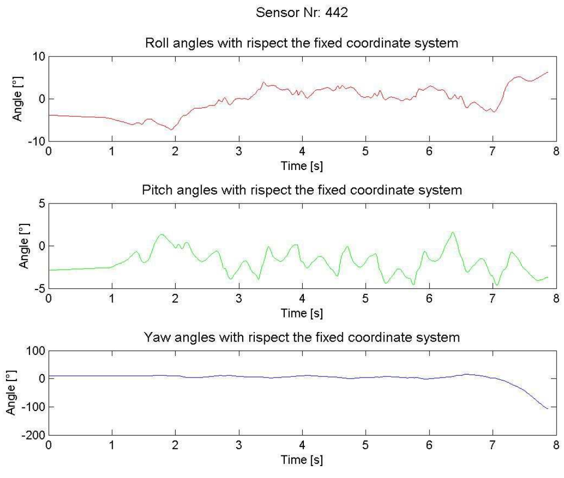

Fig 76: Sacrum movement (Segment angles)

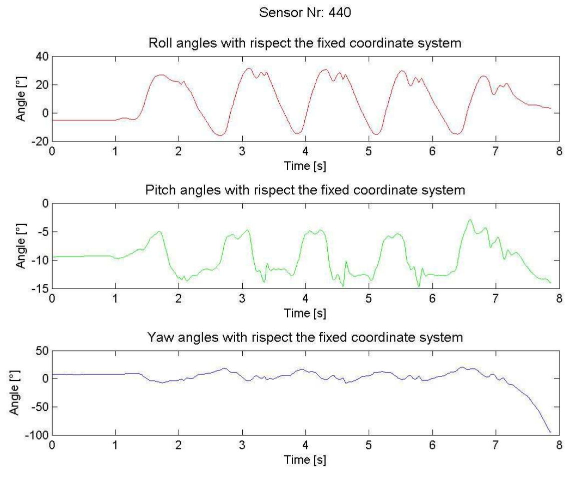

Fig 77:Left Thigh movement (Segment angles)

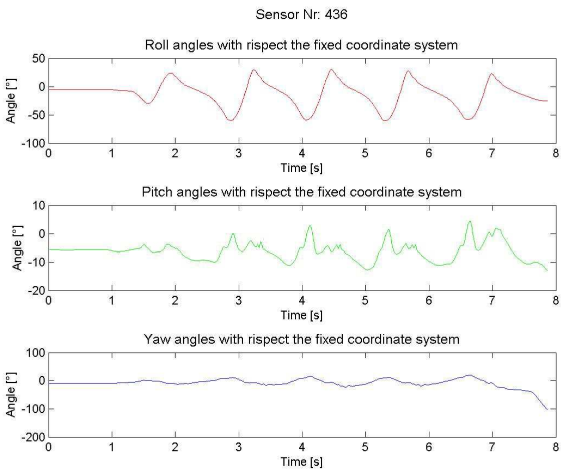

Fig 78: Left Shank movement (Segment angles)

The first graph represents sacrum's movement during walk: the sensor 442 was placed too high, indicatively to L4-level because in the subject's iliac crests were placed markers. For this reason the movements recorded were not as expected. Other two graph reported the movements of the left Thigh and the left Shank. Below are inserted 438 and 439 sensors' graphs with, in black, the BTS *Segment angles*, and the *Segment to Segment angles* are shown on the figure 76:

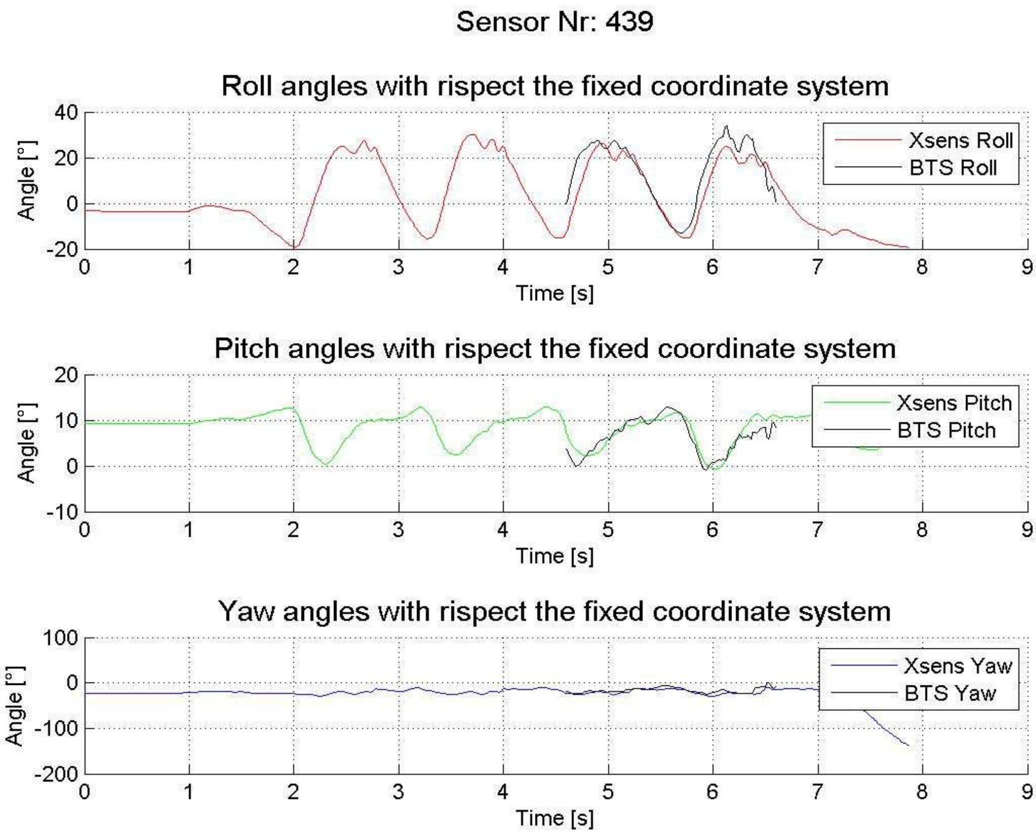

Fig 79: Thigh Segment angles comparison

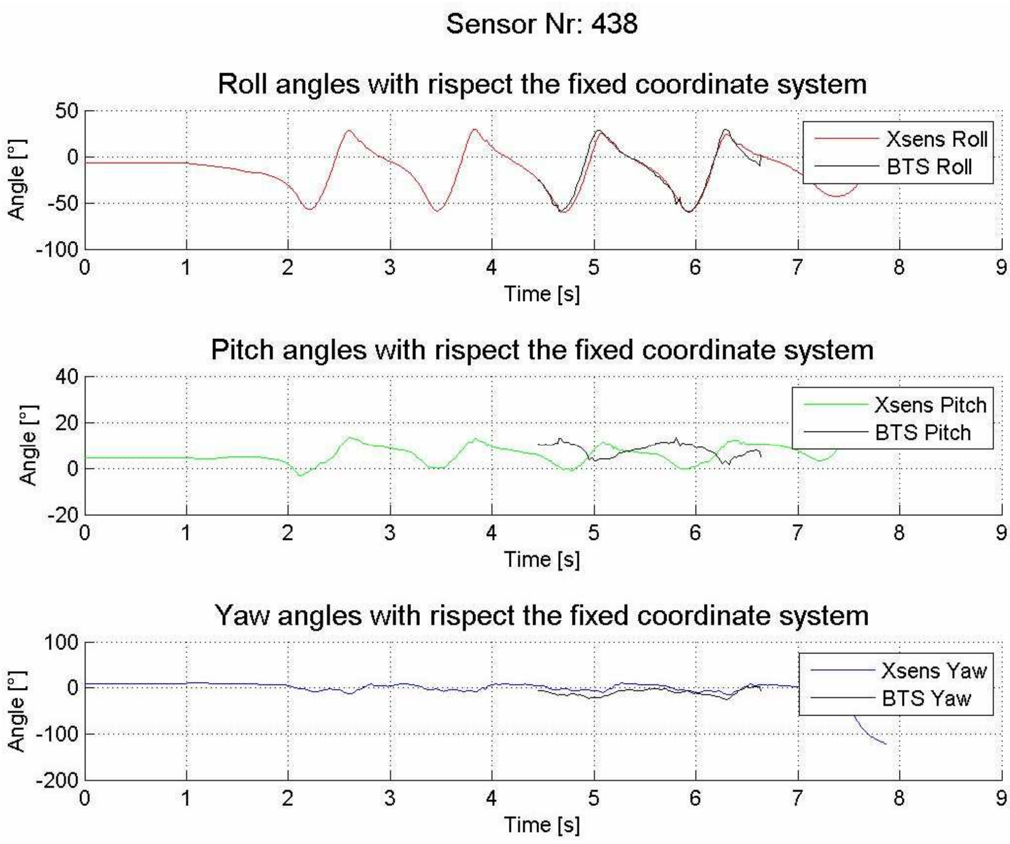

Fig 80: Right Shank Segment angles comparison

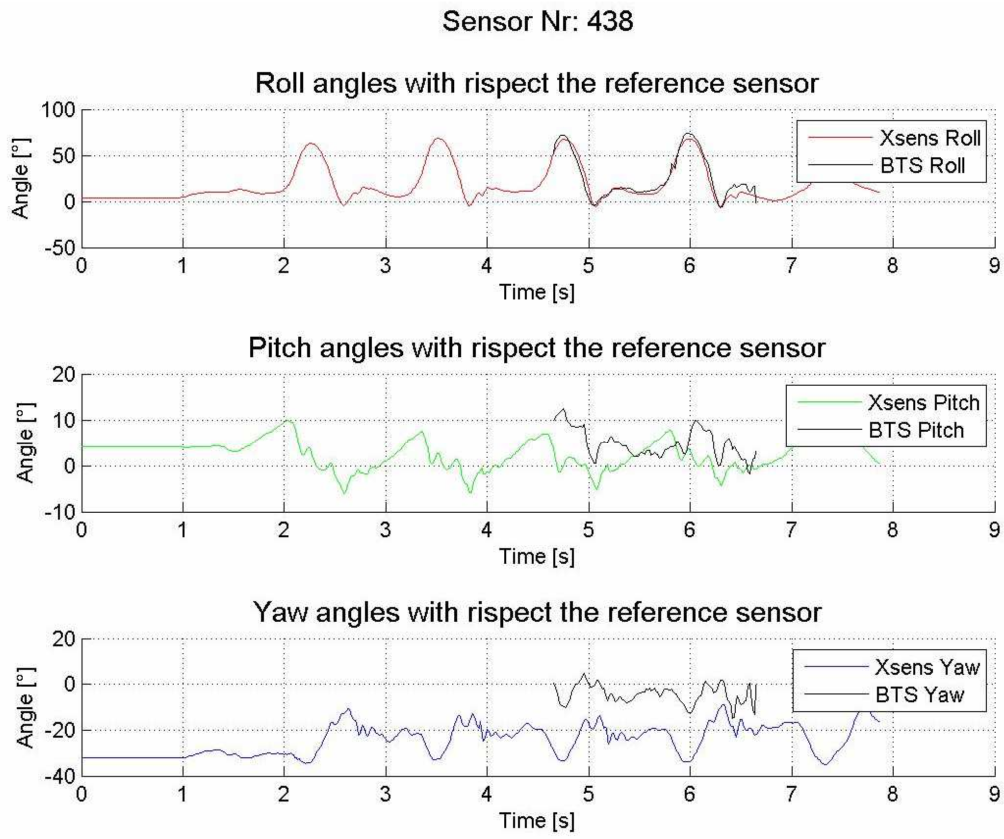

Fig 81: Shank to Thigh Segment to Segment angles comparison

How it can see in the previous graphs, the angles given both from Xsens and the optoelectronic system are comparable to each other. In the Y (Pitch) axis were not removed, from the plots, the Static angles weren't eliminated and the subject may have followed a non perfectly linear trajectory during the walk (only for the *Segment angles*). Due to this reasons the Xsens angles are shifted with respect to the optoelectronic angles.

The *Segment to Segment angles* are physiologically more interesting than the *Segment angles*, because they give information about motions of a body segment with respect to another body segment; therefore, for the other two gait analysis performed, it will be presented only *Segment to Segment angles*.

Following, respectively the gait analysis of the second and third gait test:

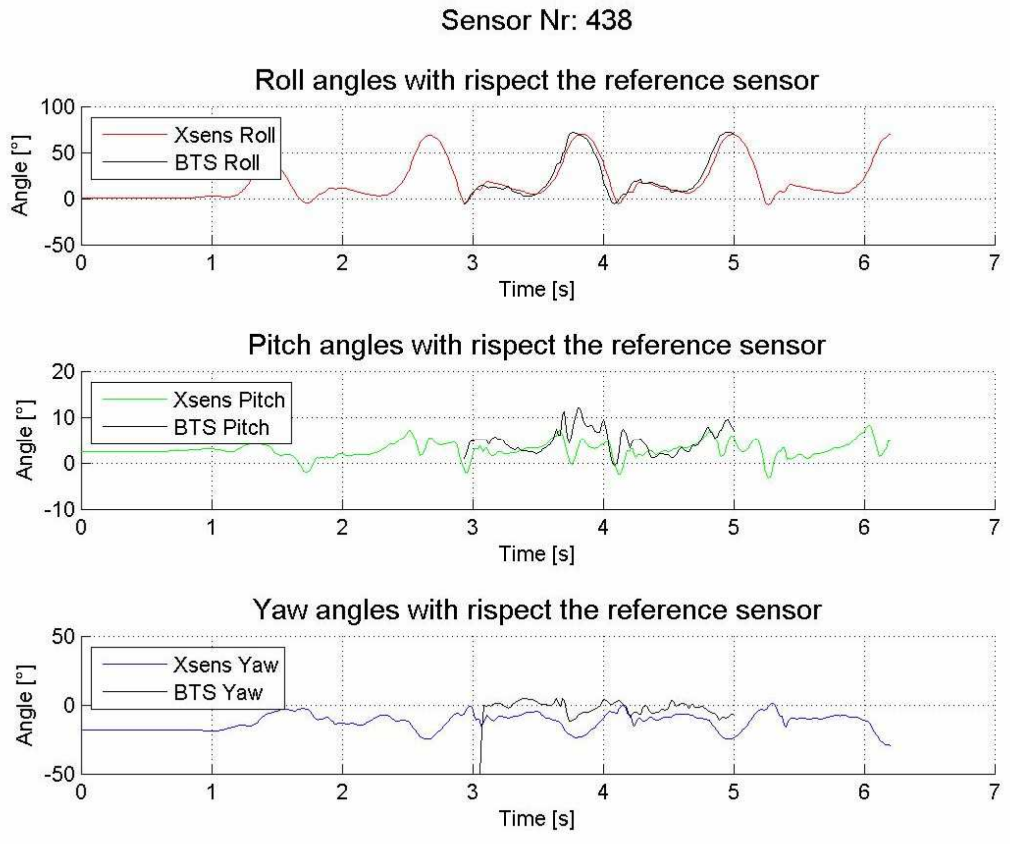

Fig 82: Shank to Thigh Segment to Segment angles comparison

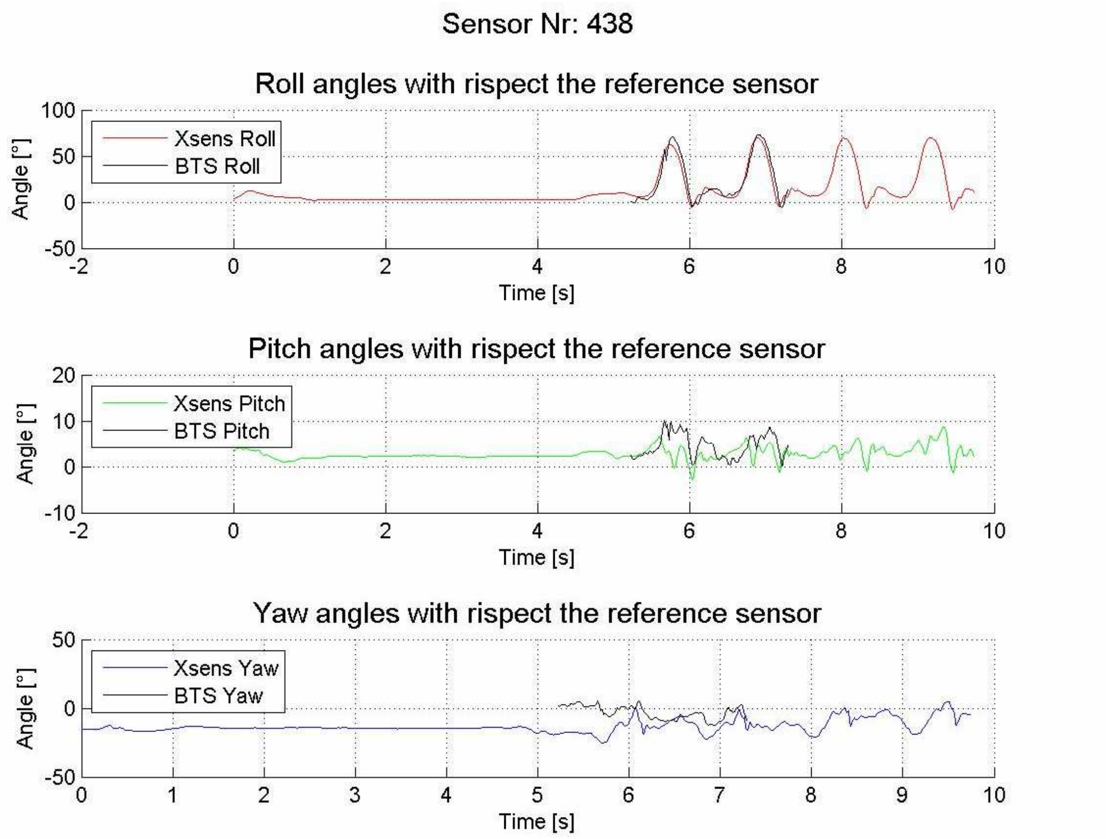

Fig 83: Shank to Thigh Segment to Segment angles comparison

As a conclusion, after analyzing the data in these graph, the optoelectronic flex-extension angles result a generally about 10° larger than the corresponding Xsens angles. Regarding the ab-adduction angles, they are generally more different from the others; however the difference, considering graphs are shifted due to reasons explained in the first gait test of this paragraph, is lower than 10°. Finally, intra-extra rotation angles are widely shifted, but in the *Segment to Segment angles* it's not considered the motion trajectory effect. This difference could be given due to disturbance or magnetic fields, however, the angles amplitude is comparable, with a difference lower than 10°.

5.4.3 Test of intensive care bed

MTws™ portability is one of the most important features of the Xsens, and it allowed to perform a test session, in an intensive care room.

The test described in this chapter was executed at an intensive care room at the Padua's Hospital, to record the movements transmitted to a patient, when the intensive care bed, in which he was lying, was mobilized by the hospital operators, the patient's role was recited by a volunteer workmate. Indeed, resulted some movements which not to be transmitted in the correctly to the patient, first of all the motions in which the patient's body is influenced from the gravity force without the support needed, e.g. the trunk in sit position. Another problem is the slip of the patient when a tilt movement is performed. Every movement which is not correctly transmitted, may worsen the patient's conditions. The test was performed with 5 MTws™ and 3 optical markers in order to evaluate both orientations and displacements of the subject during bed's movements.

An Alignment reset pack with a tilt of 11.5° on the Y axis was performed on the 5 MTws™ and, this operation set the same sensor coordinate system to all sensors, formed by:

- *X* parallel to the sagittal plane;
- *Z* pointing upwards;
- *Y* following the right hand rule.

Subsequently the Xsens were placed on the subject following this scheme:

Sensor	**Position**
436	Left Shank
438	Left Thigh
439	Sacrum
440	Left shoulder
442	Head (forehead)

Also the reflective markers were placed on three anatomical landmarks:

1. Left acromion;
2. Left greater trochanter;
3. Lateral epycondile of the left leg.

All the movements took take place in the *XZ* plane, because all motions were around the *Y* axis, therefore to make simpler the data analysis, the Roll and Yaw angles can be considered negligible with respect to the real motions performed around the Y axis.

Initially the subject was invited to stand in the *physiological reference position* and, to verify the correctness of the reset, the subject also rested in horizontal position on the bed was taken as a second p*hysiological reference position*. This means that for this test there are two collections of *Static angles*, one referred on the standing position and the second referred to the horizontal position.

Fig 84: Sensor placement (frontal view)

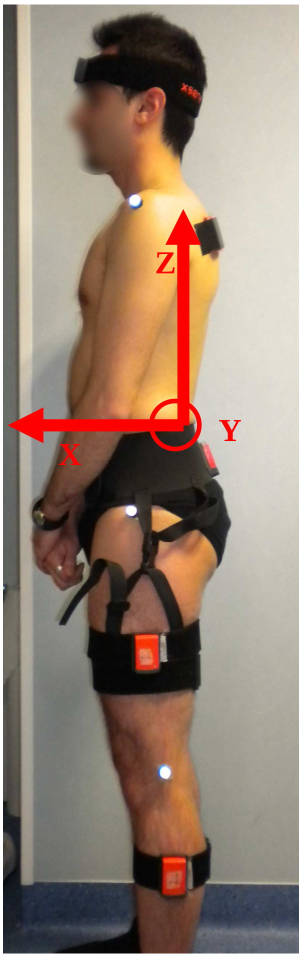

Fig 85: Sensor placement (side view)

Fig 86: Sensor placement (back view)

Static angles returned during vertical position					
	Sensor 436	**Sensor 438**	**Sensor 439**	**Sensor 440**	**Sensor 442**
Pitch (Θ) [Deg]	37.22	23.54	2.27	4.27	31.14

Static angles returned during horizontal position					
	Sensor 436	**Sensor 438**	**Sensor 439**	**Sensor 440**	**Sensor 442**
Pitch (Θ) [Deg]	90.44	88.20	-72.16	-66.82	-68.39

These data shown immediately an incongruence because two of five sensors had returned a positive Pitch angles. When the subject was in horizontal position on the bed, *Y* axis rotation was about -90 degrees with respect to the vertical physiological reference position, if the *Y* axis was in the expected direction. These discordances can be due only to problems resetting being performed: later on it was found that in the bottom part of the bed there were two permanent magnets. The magnetic fields produced by the magnets, may have been the cause of these three sensors wrong reset. However, this inconvenience was fixed during the analysis data step and the trend of the graph can be considered as more correct.

The most interesting movements done, were:

0° trunk and 0° leg	30° trunk and 0° leg	45° trunk and 0° leg	30° trunk and 0° leg	30° trunk and 10° leg	0° trunk and 0° leg

In the following table there is a summary of averages of *Static angles* returned from MTws™ which represent the subject movements in according to the intensive care bed movements:

	442 (Head)	**440 (Left shoulder)**	**439 (Sacrum)**	**438 (Left Thigh)**	**436 (Left Shank)**
Trunk at 30°	-25,9	30,89	28,31	6,13	2,13
Trunk at 45°	-40,8	38,38	31,33	4,47	4,64
Trunk at 30° and leg at 10°	-31,9	23,46	18,73	2,88	6,74
Trunk and leg at 0°	-4,6	2,85	-3,7	-3,85	-3,47

In the next page are reported the graphs of angle values returned by MTws™ with a graphical representation of the bed movements.

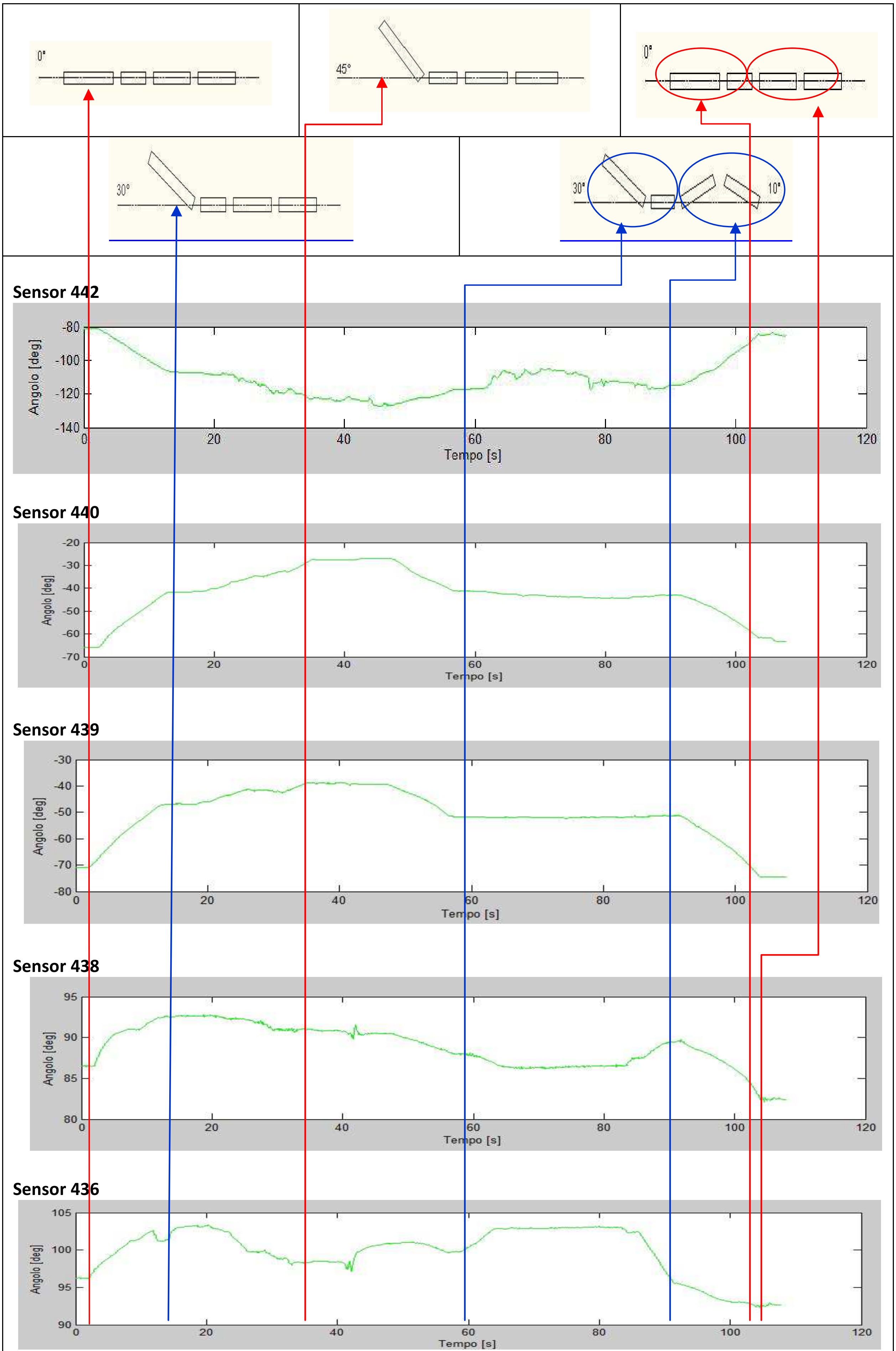

Fig 87: Comparison between subject and bed movement

The values found show initially that movements transmitted to the subject are generally lower than the bed’s movements. This result was expected, initially because the mattress can not transmit the total bed’s movements to the subject, but, also because some parts of motion are lost due to the subject’s movements on the bed, as slip effect. Moreover the data show a link between trunk and leg movements, even if these movements were performed separately.

Test like this can allow to design intensive care beds more and more comfortable for the patient, focusing attention on the patient and evaluating the real effect on patient of bed's movements which, like shown in this test, are not perfectly coincident.

CHAPTER 6

Joint anatomical axes

6.1 Joint anatomical axes method

As previously in paragraph 3.3, Xsens system measure *Unit Segment angles* or *Segment to Segment angles*, instead the optoelectronic system measures also *Joint angles*. The MTws™ are not placed on specified points and they are affected by skin and muscle artifacts, therefore the *Segment to Segment angles* calculated by Xsens, are different with respect to the real angles described by the bones movement. The optoelectronic system, using anthropometric data and the specific markers placement, can reconstruct angles, called Joint angles, with low level of artefacts due to skin and muscle effects. Obviously, in clinical application of motion analysis, the data must have the lower component of artefacts as possible. Due to this reasons, it was developed a method to calculate the Joint angles, or angles which can give more significant information than the *Segment to Segment angles*. To obtain angles described by the anatomical movements it’s necessary to create a joint reference system composed by anatomical rotation axes, with respect to which calculate angles to be determined.

It is possible to create a coordinate systems placed on proximal and distal segments or coordinate frames placed on joints. Regarding the Xsens, the system can return also the angular velocity data that can be represented by a vector characterised from direction and orientation, indeed the three vector's components *X*, *Y* and *Z* are given in output. The angular velocity vector direction is perpendicular to the plane of rotation with orientation that follows the right hand rule. By definition, the direction of angular velocity vector is equal to the rotation axis direction, therefore, applying this definition to distal motions with respect to a proximal body segment, using angular velocity vector it can be found the anatomical axis around which motions are performed. Distal and proximal motions are considered with respect to the joint.

The joint coordinate system is composed by anatomical rotation axes and with this method, it is possible to calculate it. For a casual movements the rotation axis don't gives important biomechanical information, but if the subject performs uni-axial motions around the physiological axes (e.g. flex-extension, intra-extra rotation etc.), the angular velocity vector's direction must be equal to the corresponding anatomical axis direction of the motion performed. To obtain the knee coordinate system following this method, necessary independent motions are flex-extension, intra-extra rotation and ab-adduction. At this point, to obtain significant data, movements must be as much more uni-axial as possible. Due to this reason, two solution were adopted: creating a mechanical device which forced the movements only around the axis to find or to define specific motions to perform in particular positions minimizing unwanted movements. The use of mechanical device was discarded because it is a more complex approach (and it could require a long time), but if the precision required are very high, with such devices, the movements must be perfectly uni-axial. In the other hand this approach would force the subject's motions and eventually disorders wouldn't be identified.

The second solution, based on physiological, will be explained in the following paragraph.

6.1.1 Basic movements

The subject performed specific mono-axial movements, minimizing unwanted ones as previously explained. Positions are defined according to the joint motions, e.g. to find the knee coordinate system,designed positions are:

- Sit on a table to perform the flex-extension and the intra-extra motions;
- Standing position to perform the ab-adduction movements;[6]

Data acquired during tests were affected by artefacts due to thigh's muscles activation, so the calculated subject's joint rotation axes aren't equals to anatomical ones. Due to this, calulated axes are not quoted here.

The standing position is the designed position to find the hip coordinate system.

[6] Precisely, the ab-adduction knee's motions should be performed with the subject in prone position, but this aim wasn't improved, and the tests were mainly performed to verify the method

Fig 88: Calf intra-extra rotation

Fig 89: Knee Flex-extension

Fig 90: Hip ab-adduction

Fig 91: Hip flex-extension

Fig 92:Hip intra-extra rot.

Basic movements defined upward are necessary to create the joint coordinate system, and they are defined according to the joint's motions. Due to this reason they could change from joint to joint.

6.2 Matlab software to calculate rotation axes

Even for this aim a Matlab software which allows to analyze data was created. Thanks to the modularity of the software created for the comparison, some functions exposed before are still used for this application and the angles returned are the input of the new functions which calculate the rotation axis:

- *Time resize function*: allows to redefine the length of the signal, to perform analysis on the selected motion. This function is fundamental for the correct operation of the motion axis function and to obtain less data to compute, because for every sample is defined an angular velocity vector;

- *Angular velocity function:* was inserted due to the incongruence between orientation data and angular velocity data (explained in the 4.2.4 paragraph). In this function is calculated (following the definition) the angular velocity data starting from the *Segment to Segment angles* data. The algorithm which perform the derivative was created with this scheme:
  - The discrete derivative of the first (*n=1*) sample is calculated using the definition (the first forward difference):

$$\dot{\Phi}(1) = \Phi(n+1) - \Phi(n)\left(\frac{(n+1)-n}{fs}\right)^{7}$$

  - For the data between second to second-last samples, the discrete derivative is calculated with this resolution:

$$\Phi(n+1) = \Phi(n+2) - \Phi(n)\left(\frac{(n+2)-n}{fs}\right)^{8}$$

  - The discrete derivative of the last (*n=length(Φ)*) sample is calculated using the definition (the first forward difference):

$$\dot{\Phi}(n) = \Phi(n) - \Phi(n-1)\left(\frac{(n+1)-n}{fs}\right)^{9}$$

  This resolution allows to obtain the angular velocity data expressed in the right coordinate system: the comparison with the angular velocity given in output from Xsens has revealed slight differences, mainly due to the data filtering done by Xsens;

- *Motion axis function:* performs a comparison between the *X*, *Y* and *Z* components of the angular velocity vectors and the highest one is selected. The comparison is performed by calculating the average of absolute values of each component, and by taking the axis of higher value of angular velocity as the rotation axis. This assumption may be correct considering two parameters: performing the basic movements, the angular velocity of the motion axis should be much higher than the other two components and it is fundamental, using the time resize function, to erase each signal's segment that doesn't contain information about the motions (e.g. initial subject's positioning or other movements not required);

[7],[8],[9] *fs* is the sampling frequency and the angle Φ is taken as example.

- *Threshold function:* applies a threshold, selected by the user, to the angular velocity data. To increase the threshold effect it is applied to the vector's module and the values included between [+threshold ÷ -threshold] are erased. Indeed the low angular velocity data, refers to slower motions mainly affected by errors. Lastly, the same samples erased in the vector's module are erased in the axis of higher motion, recognized with the *Motion axis function;*

- *Rotation axis function:* calculates the rotation axis from the angular velocity vectors. The rotation axis can be considered as the average of all angular velocity vectors of the axis recognized with the *Motion axis function.* To find the average of these vectors, the averages of *X*,*Y* and *Z* components of every vectors are calculated, and the rotation axis, which is equal to the anatomical rotation axis, should be identified by the three coordinates found. The anatomical rotation axis found is expressed in the coordinate system of the sensor taken as reference. E.g. to calculate the flex-extension rotation axis of the knee, the subject must be invited to perform the flex-extension movements, trying to limit others motions, and the angular velocity vector must be calculated from Shank to Thigh *Segment to Segment angles*, so that the direction of the angular velocity vectors are coincident with the knee flex-extension axis.

6.3 Validation test

The electrogoniometer test can be used as validation test for the method used to find the rotation axis: indeed for all test the electrogoniometer had performed movements around the Z axis, because all motions were performed on the horizontal surface. Analyzing data steps are:

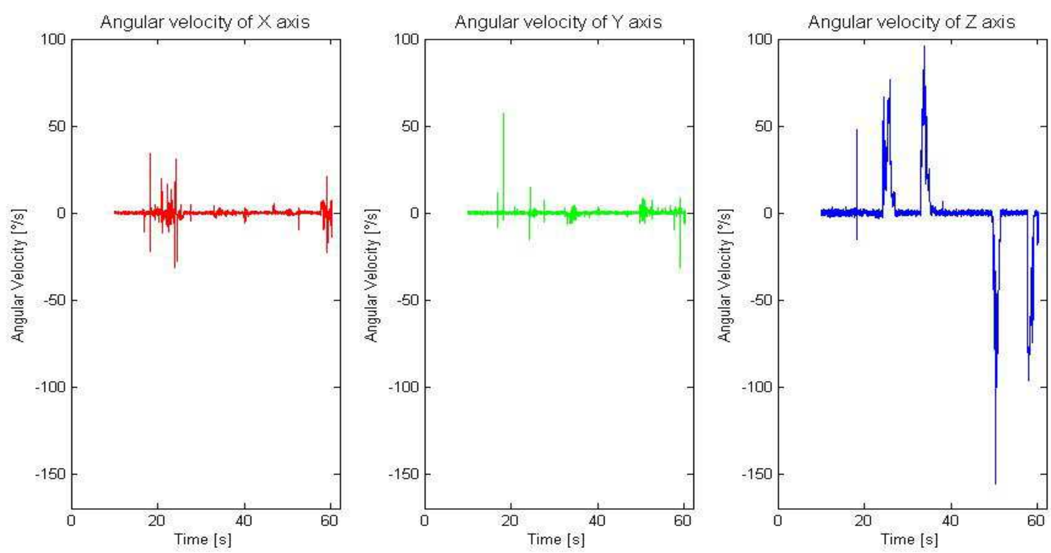

Fig 93: Angular velocity diagram

This graph show the angular velocity data returned from the angular velocity function. The figure below highlight the correspondence between orientation and angular velocity data:

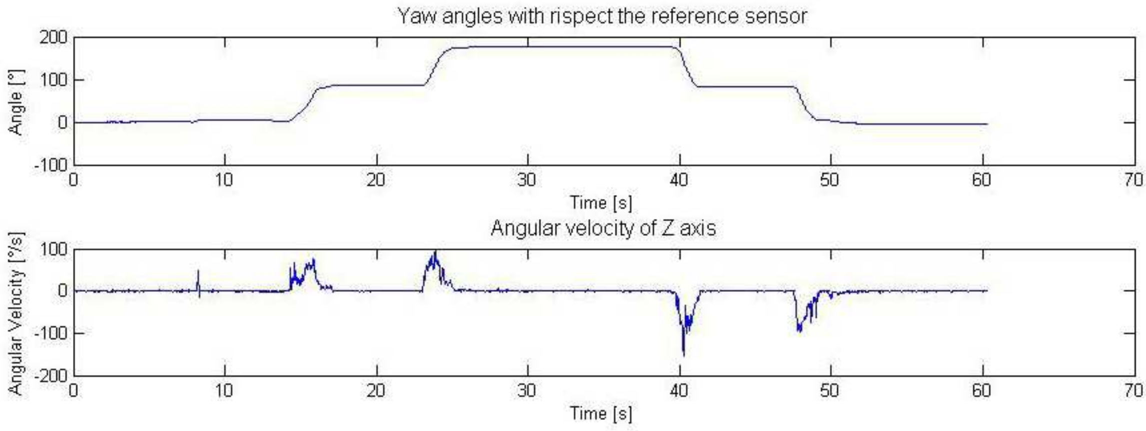

Fig 94: Correspondence between orientation and angular velocity data

To erase the small peak at 8.23 seconds, the *Time resize function* is used and the signal up to 10 seconds is cut. The graph below represent the angular velocity vectors:

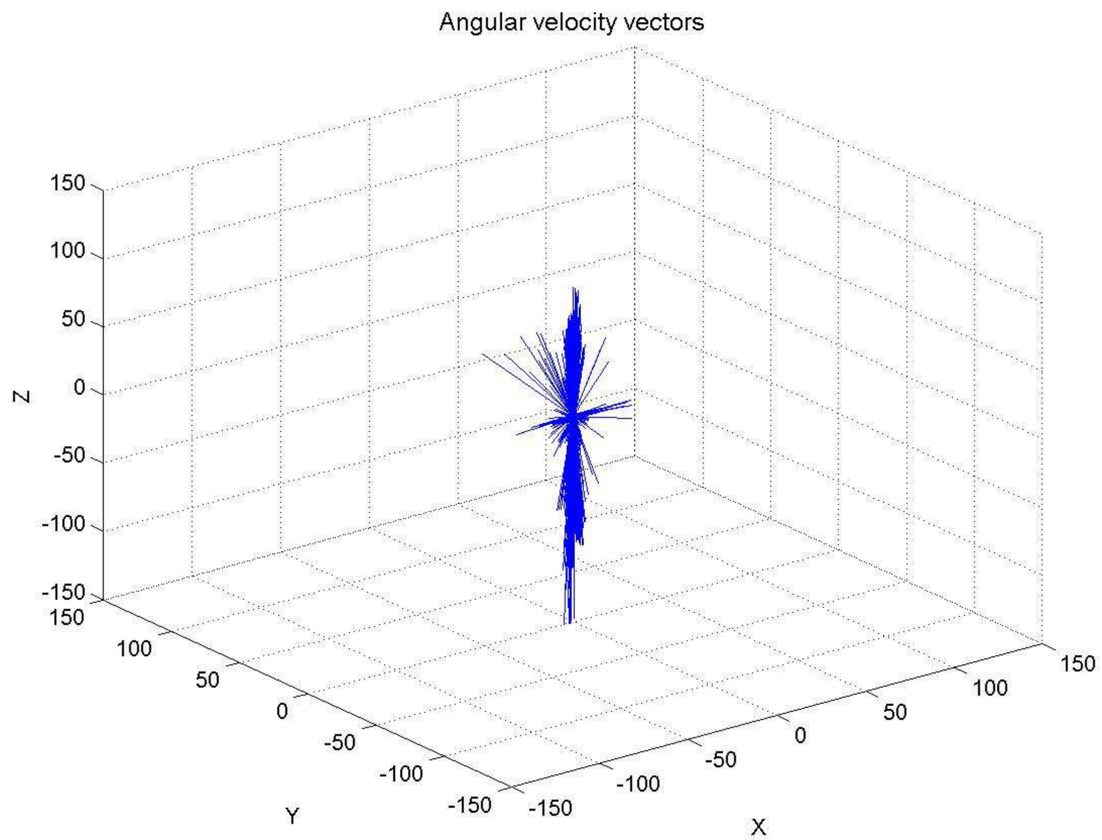

Fig 95: Angular velocity vectors

It is possible to notice that most of vectors are in the Z axis direction, but there are some lower vectors in the other directions. To maintain only the higher vectors, a threshold was inserted by the user. A 40% of the peak value threshold was inserted in this example:

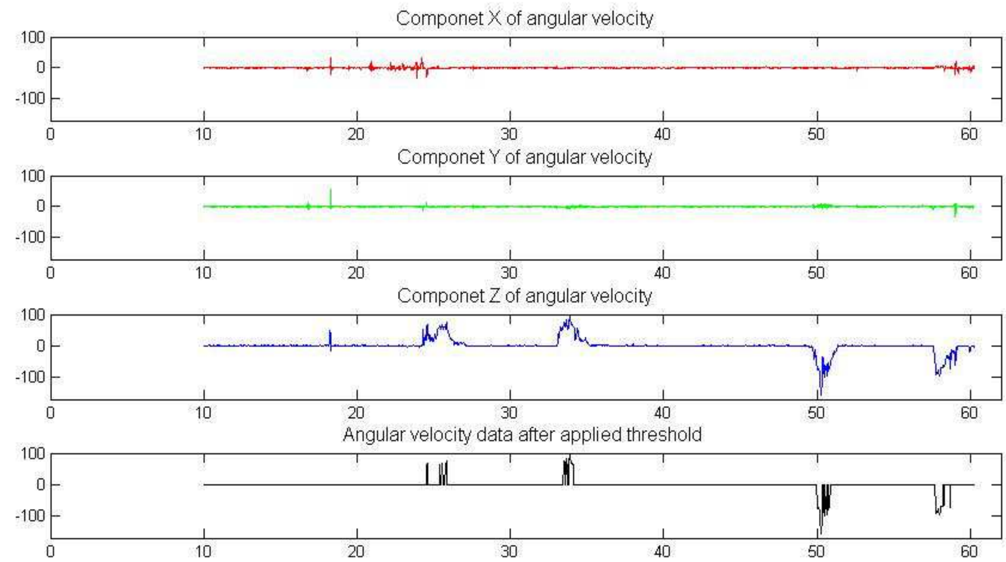

Fig 96: Component of angular velocity vectors and the threshold applied

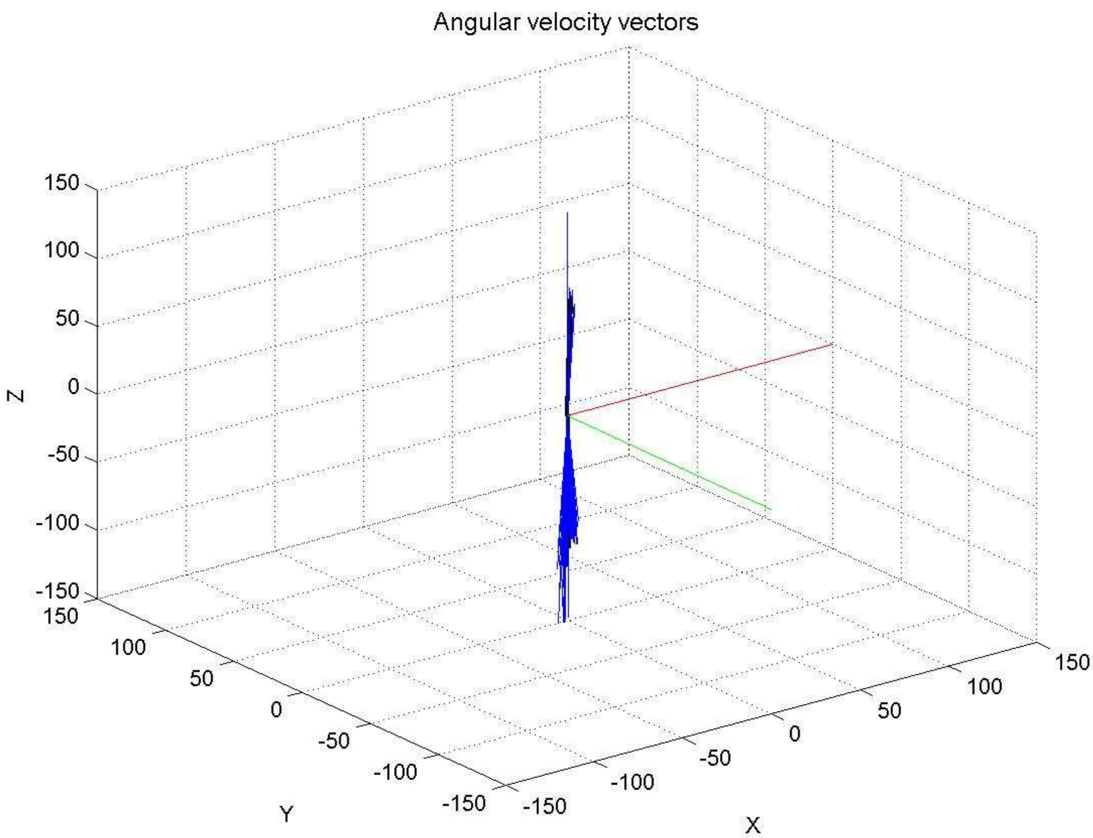

Fig 97: Angular velocity vectors of threshold data

All vectors lower than the threshold are erased, and, using the rotation axis function the rotation axis is calculated:

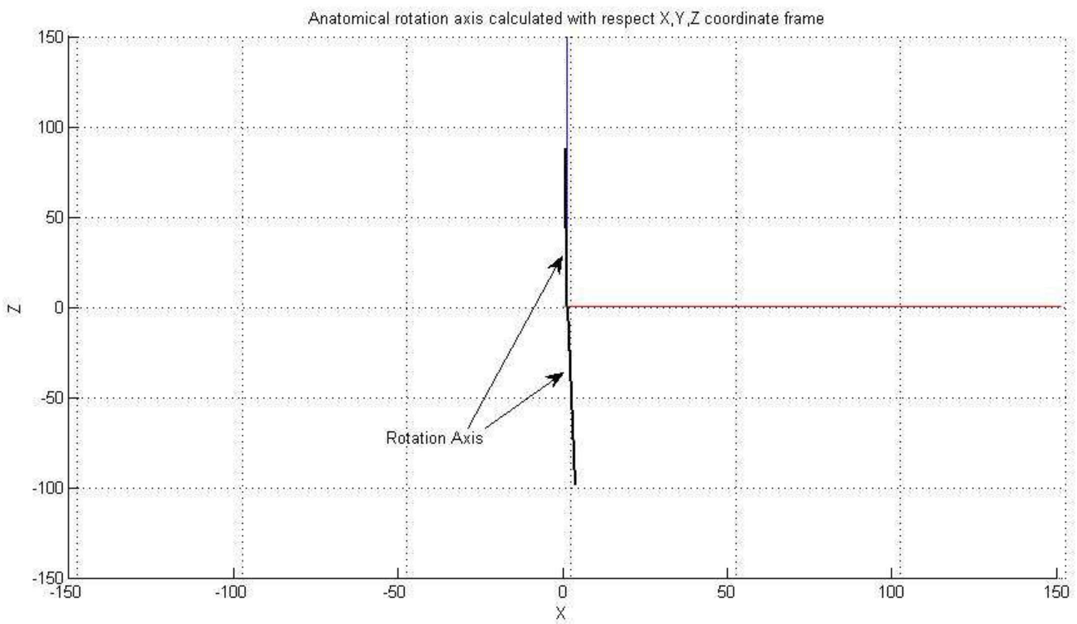

Fig 98: Rotation axis founded (XZ plane view)

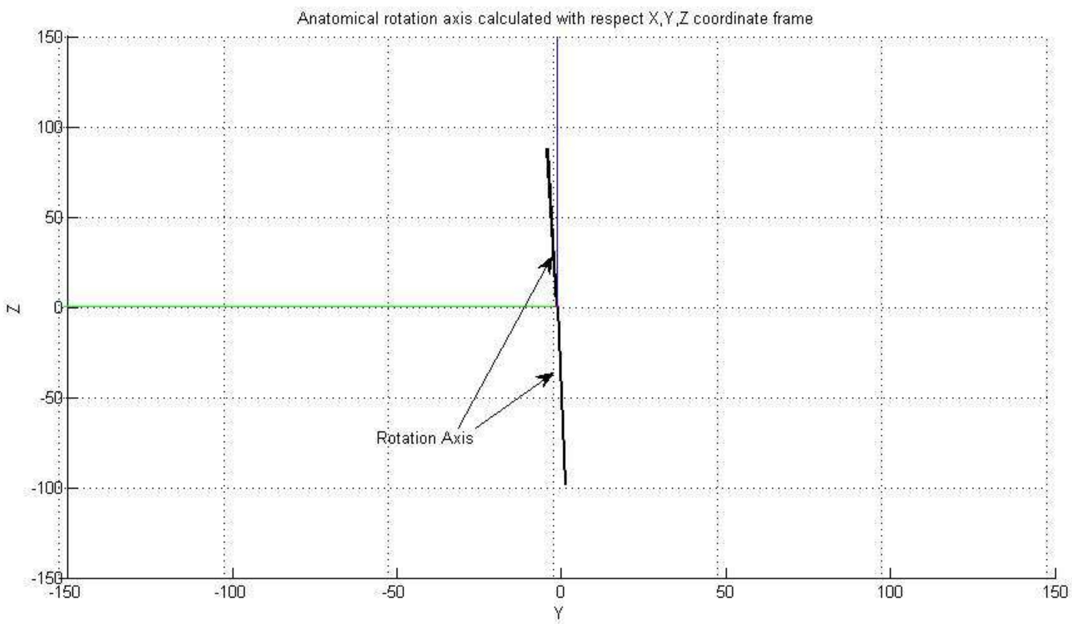

Fig 99: Rotation axis founded (YZ plane view)

The rotation axis calculated, as is can see in the previous graphs, is not perfectly coincident to the Z axis, because the superior electrogoniometer's stem was flexed due to the weight of the MTw™ placed on the tip. Considering this error during the test, the rotation axis calculated coincides with the one expected, therefore this test had confirmed the correctness of the method used.

CHAPTER 7

Conclusion

7.1 Conclusions

Inertial sensors, like the Xsens MTw™ used for tests made, are having rapid diffusion in several application areas, from biomechanics field to entertainment. Both portability and easiness of use are the main features behind this rapid commercial expansion.

The methodologies developed during this work, based on a particular reset approach and a specific angles sequence resolution, allows to perform comparison between Xsens MTw™ product and BTS optoelectronic system.

The analysis of test demonstrates that the two systems have a comparable accuracy, with a difference of about 3 degrees calculated during a uni-axial test. Regarding 3D tests, as gait analysis, the Flex-Extension's graph generally can be superimposed with an almost perfect matching and, in the Ab-Adduction and Intra-Extra movements, the error remains lower than 10 degrees. Generally, to estimate an healthy motion, a range of angles is considered physiological. This range changes with different motions, but it may vary depending on movement's phases. In figures below the range of angles considered physiologically healthy for knee motions is represented:

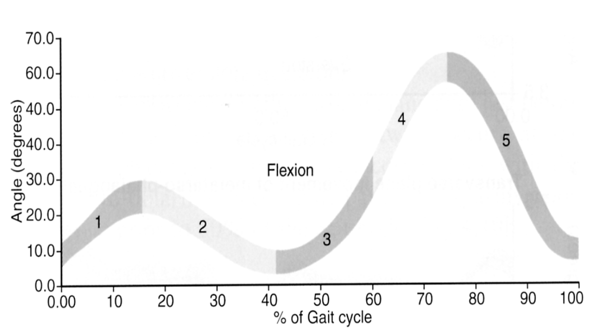

Fig 100: Knee flex-extension

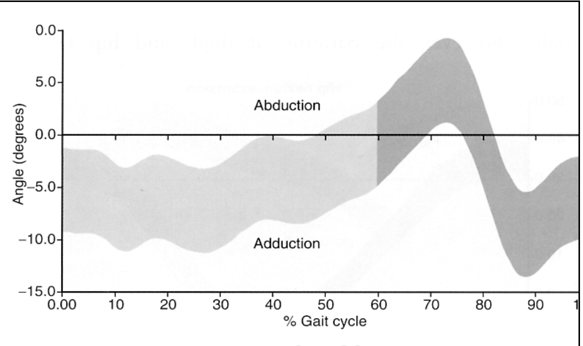

Fig 101: Knee Ab-Adduction

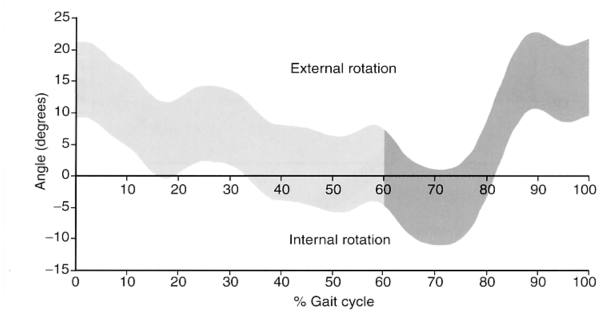

Fig 102: Knee Intra-Extra rotation

As it can be seen, in the Flex-Extension's graph the range of physiological angles is set of about 5÷10 degrees.

This consideration ensures that, considering future developments of the Xsens MTw™ technologies, it may be even possible to perform clinical trials. Anyway the MTw™ are rather used when the movement naturalness is considered more important than the accuracy, indeed it allows to record ordinary motions performed in the everyday environment. However, the method developed during this work may be difficult to apply to movements that have comparable motions in each axes. In this case it can be difficult to identify a principal motion axis and then the correct direction to set the *X* axis during the reset. If this problem should arise, the motion analysis can still be performed applying this method, but the movement must be decomposed and analyzed separately for each axis.

Nowadays, the Xsens MTw™ can’t create joint anatomical coordinate systems and can't calculate the corresponding angles. Probably this is the main difference between the two systems. Finally, it shall be interesting to perform an overall comparison between the inertial Xsens MTw™ product and the BTS optoelectronic system:

Features	**Xsens MTw**	**BTS Optoelectronic**	**Note**
Accuracy	*4*	*5*	The tests made using the method developed, gave comparable results
Subject preparation	*3*	*1*	The number of markers is generally larger than MTw, the placement requires anatomical knowledge

Portability	*5*	*1*	The optoelectronic system needs six or more cameras, acquisition systems and pc and it produces a small calibration volume
Ease of use[8]	*3*	*2*	The BTS system calibration requires some time
Anatomical information[9]	*3*	*5*	The Xsens, nowadays, can't give anatomical information with the same accuracy of the optoelectronic

In the previous table the range of evaluation was defined between 1 and 5[10]. Main features of the optoelectronic system remain the accuracy and the anatomical data information: on the contrary the Xsens main advantages are the portability and the subject preparation. However results of this work have highlighted that the Xsens' accuracy is comparable to the optoelectronic system's accuracy, therefore this parameter encouraging the use of Xsens for the biomechanical applications. Anyway, the MTw™ could change the way to perform Motion Capture recreating the laboratory in the daily life.

7.2 Future developments

Regarding the technical data, a future development may the use of the quaternion Xsens' output mode as an orientation representation. This implementation shouldn't suffer from mathematical singularity due to the Euler "aerospace" angles definition.

Concerning the Matlab software developed during this work, it might shall become standalone, to allow its use independently of Matlab's programming environment. Moreover it should be improved with an user friendly graphic interface which makes simpler and more intuitive performing the data analysis with this software. Finally, adding the data returned by Xsens to the subject's anthropometric data, it will be possible to reconstruct a 2D model of subject and revise the subject's movements using a graphical 3D environment.

[8] This term of comparison regarding only the Motion Capture step
[9] In this term of comparison is considered the ability of a system to give in output data as possible closer than the real anatomical movements
[10] Evaluation is based on the experience acquired during this work

Another next step which can be done regarding the Xsens use, is to get access to all data and configurations of each MTw, developing a software that fully utilizes the SDK's capabilities.

The most clinically interesting future development would be to create a method for defining joint coordinate systems using the Xsens MTw™ product. The method explained in Chapter 6, may be the starting point because the joint coordinate system must be formed by anatomical rotation axes. The main problem regarding this system is it has not orthogonal axes, but, once defined, the rotations about these axes are anatomically meaningful. This approach, in addition to being an important step for Xsens motion analysis applications, might decrease the larger difference of diffusion between Xsens inertial sensor and stereophotogrammetric system.

CHAPTER 8

Bibliography

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8.2 Bibliography

Wu G. and Cavanagh P.R. (1995), ISB recommendations for standardization in the reporting of kinematic data. Journal of Biomechanics 28, 1257-1261

(2002), ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion – part I: ankle, hip and spine. Journal of Biomechanics 35, 543-548

Wu G, van der Helm F.C.T., (DirkJan) Veeger H.E.J., Makhsous M,
Van Roy P, Anglin C, Nagels J, Karduna A. R., McQuade K., Wang X.,Werner F.W., Buchholz B (2005), ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion – part II: shoulder, elbow, wrist and hand. Journal of Biomechanics 38, 981-992

Cappozzo A., Catan A., Della Croce U., Leardini A., (1995), Position and orientation in space of bones during movement: anatomical frame definition and determination. Clinical Biomechanics 10, 171-178

Cappozzo A., Catan F., Leardini A., Benedetti M.G., Della Croce U., (1996), Position and orientation in space of bones during movement: experimental artefacts. Clinical Biomechanics 11, 90-100

Cappello A., Cappozzo A., La Palombara P.F., Lucchetti L., Leardini A., (1997), Multiple anatomical landmark calibration for optimal bone pose estimation. Human movement science 16, 259-274

Cappozzo A., Della Croce U., Leardini A., Chiari L., (2005), Human movement analysis using stereophotogrammetry Part I: theoretical background. Gait and Posture 21, 186-196

Della Croce U., Leardini A., Chiari L., Cappozzo A., (2005), Human movement analysis using stereophotogrammetry Part 4: assessment of anatomical landmark misplacement and its effects on joint kinematics. Gait and Posture 21, 226-237

Cappello A, Cappozzo A, La Palombara P. F., Lucchetti L, Leardini A, (1997), Multiple anatomical landmark calibration for optimal bone pose estimation. Human Movement Sience

Cutti A. G., Giovanardi A., Rocchi L., Davalli A., Sacchetti R.(2008), Ambulatori measurement of shoulder and elbow kinematics through inertial and magnetic sensors. Med Bio Eng Comput 46, 169-178

AIS Lab, Università degli studi di Milano, 2007.

Mtw User Manual, © Xsens Technologies B.V.

M. J. Roberts, Signal and Systems. McGraw Hill

Vaughan C.L., Davis B.L., O'Connor J.C. "Dynamics of Human Gait", Second Edition. Kiboho Publishers, Cape Town, South Africa.

J. Richards. "Biomechanics in Clinic and Research", Churchill Livingstone, Elsevier, 2008.

Human movement analysis using stereophotogrammetry.Part 1: theoretical background, Aurelio Cappozzo et Al., Gait and Posture 21 (2005) 186–196.

8.3 Webography

http://www.motion-capture-system.com/resources/history.html

http://www.kingston.gov.uk/browse/leisure/museum/collections/muybridge/about_muybridge.htm

http://www.ctie.monash.edu.au/hargrave/marey.html

http://web.mit.edu/invent/iow/edgerton.html

http://accad.osu.edu/~bwindsor/AC694Z_Spring2004/Class1_brian_bw.pdf

http://www.bium.univ-paris5.fr/marey/

http://www.dartfish.com

http://www.arielnet.com/start/

http://www.btsbioengineering.com

http://mafija.fmf.uni-lj.si/seminar/files/2007_2008/MEMS_accelerometers-koncna.pdf

http://www.engineerguy.com/bio.htm

http://labspace.open.ac.uk/mod/resource/view.php?id=420014

http://www.pyroelectro.com/tutorials/accel_intro/

http://clifton.mech.northwestern.edu/~me381/project/done/Gyroscope.pdf

http://www.sensorsmag.com/sensors/acceleration-vibration/an-overview-mems-inertial-sensing-technology-970

http://embeddedsystemnews.com/stmicroelectronics-introduces-a-new-family-of-single-and-multi-axis-mems-micro-electro-mechanical-systems-gyroscopes.html

http://www.motion-capture-system.com

http://www.xsens.com/en/company-pages/company/human-mocap

http://www.shoppingtrolley.net/anatomy-and-physiology-2b.shtml

http://www.btsbioengineering.com/

"Virtual Figure Drawing Studio (Male) 1.08a" is the software used to create the figure 24, 25, 26 and 27.