Classification of trunk motion based on inertial sensors

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RESUMEN

Por mucho tiempo en la ingeniería se ha trabajado para la valoración y prevención de desórdenes musculo esqueléticos de la espalda. El uso de sistemas de captura de movimiento es una de las técnicas más utilizadas en este ámbito, considerada el estándar, es un sistema de alto costo y limitaciones considerables. El uso de sensores de inercia en los últimos años ha llegado a ser muchos más frecuente gracias a los avances tecnológicos que lo han llevado a ser más accesible y compacto. Este proyecto se basa en el uso de sensores de inercia para la clasificación de movimientos de la espalda, lo cual ayuda a la valoración y prevención de desórdenes musculo esqueléticos.

En el presente texto, se presenta todo el proceso de desarrollo de un sistema para la identificación de movimientos de la espalda, mediante el uso de las señales de los sensores de inercia. Se presentaran experimentos y resultados del uso de un sistema de captura de movimiento comparado con el sistema de sensores de inercia. El programa propuesto para la clasificación de los tres movimientos del tronco (flexión, lateral y rotación) trae consigo importantes ventajas de fiabilidad y libertad espacial.

El sistema desarrollado permite la valoración de los movimientos del tronco. La clasificación de estos movimientos utilizando sensores de inercia es un método considerablemente mucho más portable comparado con un sistema de captura de movimiento. También, este sistema se puede usar en diferentes espacios sin mayores esfuerzos y los límites transnacionales de movimientos son mucho más amplios en comparación con sistemas de captura de movimientos. La clasificación permite la adición de nuevas características para la identificación más precisa de movimientos o posturas que permitirán una mejor valoración para la prevención de desórdenes musculo esqueléticos del trono.

Palabras clave: unidades de medición inercial, desordenes musculo esqueléticos, sistema de movimiento, clasificación.

ABSTRACT

In the engineering field, many research has been following the way to assess and prevent musculoskeletal disorders of the back. Using motion capture systems is one of the most common technics in this field. It is considered the gold standard, but considerably of a high cost and with important limitations. The usage of inertial measurement units in the last years has increased due to the technological progress which has become more accessible a compact. This project is based in the usage of inertial measurement units for the classification of back movements, which helps the assessment and prevention of musculoskeletal disorders.

This paper presents the process of development of a system for the identification of back movements, using the signal of inertial sensors. It is presented experiments and results of a motion capture system compared to the inertial system. The program proposed for the classification of the three back movements (flexion, lateral bending and rotation) brings important advantages of reliability, spatial freedom and information.

The system developed allows the assessment of the trunk movements. The classification of the movements using inertial measurement units is a method considerably much more portable compared to a motion capture system. Also, the inertial system gives the opportunity of using it on different places without big efforts and a few movement limitations compared to the motion capture system. The classification let the addition of new and different features for a more precise identification of the movements and postures. This allows a much more accurate assessment for the prevention of musculoskeletal disorders.

Keywords: Inertial measurement units, musculoskeletal disorders, motion capture system, classification.

1. INTRODUCTION

Musculoskeletal disorders are the minor physical disabilities. This condition can affect muscles, bones and joints. It generates pain and discomfort in daily activities. Among the areas that can be affected such as neck, shoulders, wrists, back, hips, legs, knees and feet. The aim of this study is focused on the assessment of trunk movements during overhead work.

Everything would change if it exists a source of information that could help prevent MSDs. A program that could be used in a large number of diverse work settings to analyze beforehand its impact. Most likely, people wait for the symptoms to pay attention of the problem. Among the symptoms may include pain, discomfort, numbness and tingling in the affected area. But, studies (Health and Safety Authority; Health and Safety Executive for Northern Ireland, 2013) have evidence that work relatedness factors, which includes repetition, force, static posture and vibration, would develop MSDs. These factors could be identified by a system like the one that is going to be explained. People do not have to wait till the affected area differs to severe, chronic and debilitating conditions.

<u>Figure 1 – Example of working posture in car industries</u>

In the assessment of the trunk movements for its prevention care, investigations has been concentrated in the last years in the loads that it is put on the trunk, causing musculoskeletal problems. Moreover, the inappropriate postures of the body, with and without load, can also create stress and disorders in the upper body parts, more intensively in the spinal cord. Beside, people are mostly submitted to this kind of upper body stress in the working areas, like during overhead work in car's manufacturing industry. This topic has been studied in different working areas such as hospital environment, car manufacturing and building construction. Since, workers or employees are submitted to do repetitive physical efforts, without any prevention or assessment in the movements they are performing (National Institute for Occupational Safety and Health, 1997).

Musculoskeletal movements, regarding upper body, have an important impact in our body health. Daily activities can start to tighten up certain muscles, shortening them or start becoming weaker, creating pain in certain areas. The causes of these effects are very different. The main reason for an average healthy person is the rapid work pace, repetitive motion, heavy physical work, lifting and forceful movements, bending and twisting, non-neutral body postures and vibration (**Figure 1**). As mentioned by National Institute for Occupational Safety and Health, it is recognized static posture, frequent bending and torsion of the trunk as risk factors for developing musculoskeletal diseases.

PRELIMINARIES

1.1 PROBLEM FORMULATION

It is required a signal processing of the inertial sensors signal, placed at the trunk, to identify flexion/extension, rotation and lateral trunk movements. The system benefits people that perform daily trunk movements. As a first stage, it will be develop a reliable approach to identify body motion, so that in a near future it will help to prevent inappropriate body postures and the development of musculoskeletal disorders.

1.2 PROJECT OBJECTIVES

1.2.1 General objective

Develop an offline classification using pattern recognition approaches implemented on the inertial sensor signals, for the identification of trunk postures.

1.2.2 Specific objectives

- Process the inertial sensor signals for the acquisition of the trunk movements for determining its position.

- Analyze the sensor signals for feature selection, in order to assess which features provide most of the relevant information.

- Develop an offline classification of the trunk movements.

1.3 THEORETICAL FRAMEWORK

As mentioned, this investigation is focus on the trunk movements. It is going to be defined the different trunk movement. That is, to take in to account the classification and assessment of the movements performed by the subject, as well as its limits. Then, a description of the inertial sensors is stated. These are the signals that are going to be analyzed and interpreted to identify the trunk motion. Sensor fusions, Quaternions, are the most relevant information extracted from the inertial sensor signals. Due to this, it is important to state its definition and applications.

This study was based on commercial and non-commercial devices, which have a similar approach and were taken in to account in important steps of the project.

Finally, it is explained the principal characteristics of feature extraction and pattern recognition to be used, allowing the prediction of a specific movement or position of the trunk.

The relationship between the musculoskeletal disorders and workplace activities, as heavy physical work, lifting and force movements, bending and twisting (awkward postures), whole-body vibration and static work postures, are some of the factors that have been studied and which have been found to be affecting the body health.

With the identification of repetitive and posture factor, the risk of back disorders is reduced considerably. Bending is defined as flexion of the trunk usually in the forward or lateral direction. Twisting is defined to the trunk rotation. Awkward postures refer to the no neutral trunk postures in extreme positions.

1.3.1 Trunk movements and limitations

For the assessment and classification of the trunk movements, the area limits that are taken in to account are based on the parameters and standards by the ISO norm and comparable standards that exist in the field of occupational health. In which, the adequate and not adequate posture of the upper body is specifically defined.

ISO 11226:2000 “Ergonomics, Evaluation of static working postures”

Flexion/Extension: Lateral bending: Rotation:

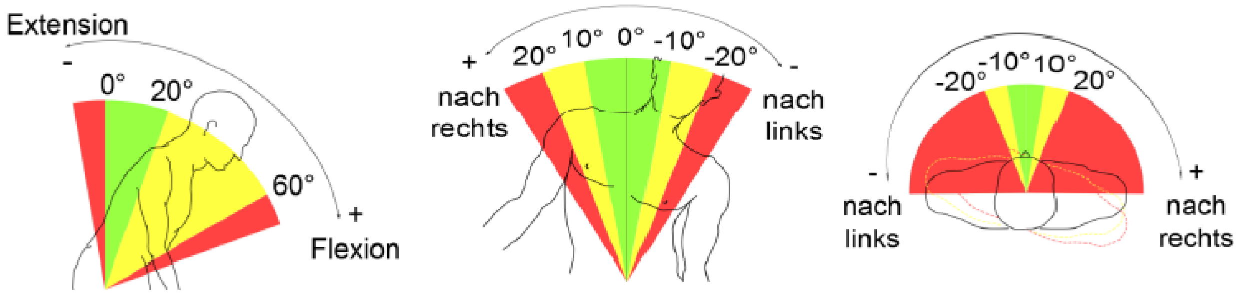


Figure 2 - Representation of the parameters and limitation of the three trunk movements to be studied (Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung, 2013).

In Figure 2 it can be appreciated the three ergonomic movements of the trunk to be studied in this investigation. The movements are the Flexion and extension, lateral bending and rotation of the trunk. Movements that have degrees where the body is not negatively affected (green zone), others where the body is at low risk (yellow zone) and in others at high risk (red zone) of developing trunk MSDs over a certain time.

The study is going to be focus on acquiring relevant information for an accurate identification of body positions and movements.

1.3.2 Inertial sensors

In general is an electronic device consisting of a microprocessor board, on-board accelerometers, gyroscopes and magnetometers. (Gowing, Ahmadi, Destelle, Monaghan, O'Connor, & Moran, 2014)

This motion system gives the direction and orientation. It fuses accelerometers, gyroscopes and magnetometers raw data Figure 3, considering it a 9-axis inertial measurement unit. The accelerometers are the translational acceleration of the sensor, the gyroscopes deliver the angular velocity, and the magnetometers the direction of the earth field at a point of the space.

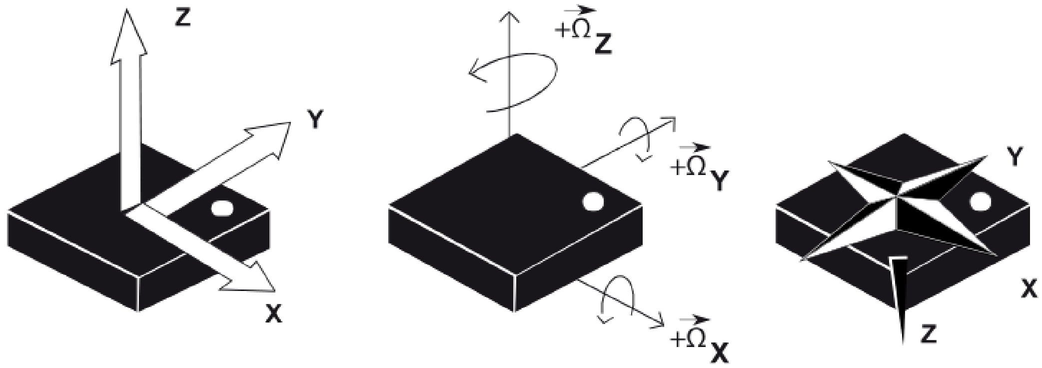


Figure 3 – Graphical representation of inertial sensors (EBVElectronik, 2015).

Inertial sensors were first used in the detection of human movements in the 1950s. However, these sensors were not commercially available until, in recent years, their performance had been dramatically improved. Since inertial sensors are sourceless, compact and light, they have been a popular choice for applications such as motion tracking, human–computer interface, and animation (Zhoua, Stoneb, Huc, & Harrisb, 2006).

The IMU used on this project were four 9-axis sensors. It had a main board were all sensors were connected sequentially by cable. Moreover, the hardware of the sensors communicated to the computer via Bluetooth. The approximated distance between the sensors and the computer were 8 meters, an advantage compering to motion capture systems. This system had a sampling rate of 50 Hz.

1.3.3 Quaternions

The most common way to represent the attitude of a rigid body is a set of three Euler angles. These are popular because they are easy to understand and easy to use. The main disadvantages of Euler angles are: (1) that certain important functions of Euler angles have singularities, and (2) that they are less accurate than unit quaternions when used to integrate incremental changes in attitude over time. These deficiencies in the Euler angle representation have led researchers to use unit quaternions as a parametrization of the attitude of a rigid body. The relevant functions of unit quaternions have no singularities and the representation is well-suited to integrating the angular velocity of a body over time. The main disadvantages of using unit quaternions are: (1) that the four quaternion parameters do not have intuitive physical meanings, (2) that a quaternion must have unity norm to be a pure rotation, and (3) less mathematical operation for calculating the orientation which is a benefit for embedded systems in speed and power consumption. The unity norm constraint, which is quadratic in form, is particularly problematic if the attitude parameters are to be included in an optimization, as most standard optimization algorithms cannot encode such constraints.

During the project it is used equations of the quaternions. The product of two quaternions represent the relative rotation from one represented orientation to the other. Its equation is:

Given:

Sensor 1:

$$Q(q) = q_0 + q_1 i + q_2 j + q_3 k \qquad (1)$$

Sensor 2:

$$P(p) = p_0 + p_1 i + p_2 j + p_3 k \qquad (2)$$

Equation 1 – Quaternion product of (1) and (2).

$$Q(q).P(p) = \begin{bmatrix} q_0 * p_0 - q_1 * p_1 - q_2 * p_2 - q_3 * p_3 \\ q_0 * p_1 + q_1 * p_0 + q_2 * p_3 - q_3 * p_2 \\ q_0 * p_2 - q_1 * p_3 + q_2 * p_0 + q_3 * p_1 \\ q_0 * p_3 + q_1 * p_2 - q_2 * p_1 - +q_3 * p_0 \end{bmatrix} \qquad (3)$$

Equation 2 – Quaternion conjugation

$$Q'(q) = \begin{bmatrix} q_0 \\ -q_1 \\ -q_2 \\ -q_3 \end{bmatrix} \qquad (4)$$

Continuing, the quaternions, as explained, do not have intuitive physical meanings, so it is necessary to convert the quaternions to Euler angles. This conversion have singularities found in the various Euler angle representations are said to arise from gimbal lock.

Gimbal lock may be understood in several different ways. Intuitively, it arises from the indistinguishability of changes in the first and third Euler angles when the second Euler angle is at some critical value. Take, for example, when the pitch angle is 90 degrees, the sensor is pointing straight up, and roll and yaw are indistinguishable. (Diebe, 2006)

However, some technics and constraints were used to reduce singularities in this application. For the calculation of the Euler angles of the trunk, the following basic equation were used.

Quaternions to Euler angle:

Equation 3 – Quaternion to Euler angles

$$Q(q) = q_0 + q_1 i + q_2 j + q_3 k \quad (5)$$

$$u_{123}(Q(q)) = \begin{bmatrix} atan2(2q_2q_3 + 2q_0q_1\ , {q_3}^2 - {q_2}^2 - {q_1}^2 - {q_0}^2) \\ -\mathrm{asin}(2q_1q_3 - 2q_0q_2) \\ atan2(2q_1q_2 + 2q_0q_3\ , {q_1}^2 + {q_0}^2 - {q_3}^2 - {q_2}^2) \end{bmatrix} \quad (6)$$

On the quaternion to Euler calculation it exists different ways to do it, this depends on the order of rotation. It means that, for example, Equation 3 u_{123} represents the rotation first in *i*, then *j* and *k*, which is presented as 1, 2 and 3 respectively.

1.3.4 Qualisys

Qualysis (Qualisys, 2013) is a 3D system based on a collection of video recordings from multiple infra-red cameras and passive markers placed on the body. After data interpolation by a software, it is obtain 3D data for motion analysis (Nicola, 2012).

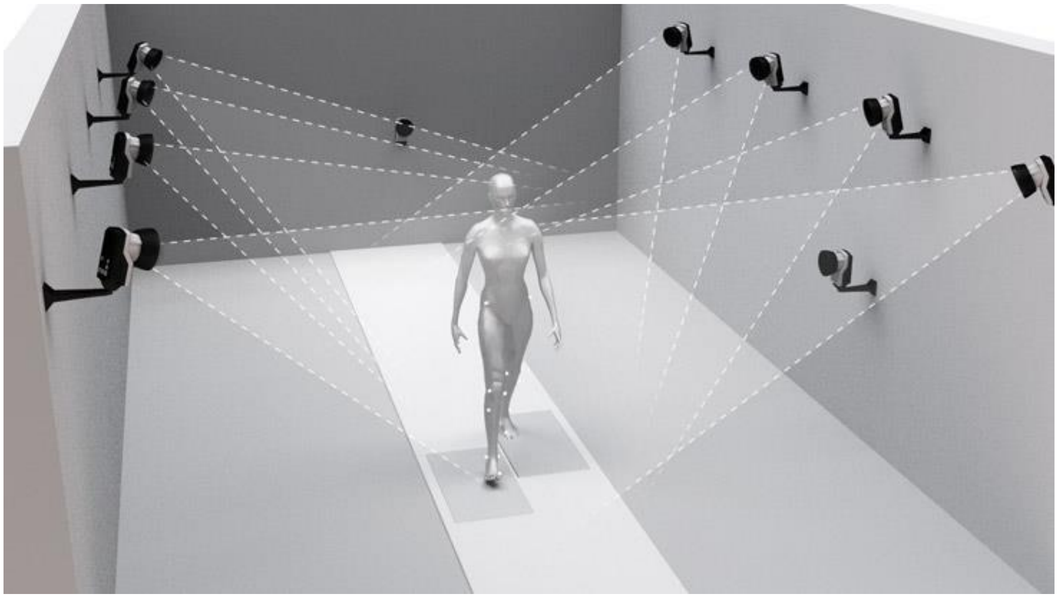


Figure 4 – Qualisys system. Cameras position and area of motion (Qualisys Motion Capture Systems).

Qualisys 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, Figure 4. Every camera can identify the direction between optical camera's center 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 colors' 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" (Nicola, 2012).

Passive markers must be placed on the subject following the position model defined, so it is 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 of, 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 called "Anatomical landmarks". These are the preferred locations of markers to verify the hypothesis before exposed.

1.3.5 Background

Musculoskeletal Disorders and Workplace Factors (National Institute for Occupational Safety and Health, 1997).

In the article “Musculoskeletal disorders and workplace factors”, is shown the association of the musculoskeletal disorder (MSD) of the upper body and the low back. These disorders are caused by the exposure to physical factors in the working area. The goal of this investigation was the relationship between MSDs and workplace activities. Among the MSD, it was studied neck, shoulder, elbow, hand/wrist and back disorders and the work influence. For our concern, focused were placed in the back MSDs.

Trunk work-related factors included heavy physical work, lifting and forceful movements, bending and twisting (awkward postures), whole-body vibration and static postures. This study provided evidence that the work-related movements have a direct influence in the development of MSDs. Thanks to this investigation, beforehand it is known that the postures that are going to be studied in the current investigation help for the assessment and prevention of MSDs.

1.3.6 State of the art

During years it has been studied the behavior of the body in different work field by vision sensors for activity recognition for body movements’ analysis (Pentland, 2000) (Gavrila, 1999). It is based on computer vision and image understanding. However, this technics have the disadvantage of being in some cases disturbing, troublemaking or privacy violated (Hong, Nugent, Mulvenna, & McClean, 2009) (Boyle, Edwards, & Greenberg, 2000). It must be added that using this approach it is complicated to monitor and analyze the posture, efforts and body loads in real-time and individually independent subjects.

In the prevention of these outcomes, it has been implemented the training of the personnel for an appropriate body motion. But, it has not provided a solution for the long term reduction of musculoskeletal disorders. The training technics do not have a permanent or constant monitoring of the movements performed by the person, turning to a subjective movement but not necessarily accurate (National Institute for Occupational Safety and Health, 1997).

Quantitative Measurement of Stressful Trunk Postures in Nursing Professions (Freitag, Ellegast, Dulon, & Nienhaus, 2007)

As it can be seen in the title of this article, the relevance of the postures exists in and out the industrial field. In this study it is presented the evaluation of the trunk influenced by stress. Yet, it is considered as an aim the awkward body postures, without load transfer, that nurses are submitted to.

For the body posture measurements have been used a personal CUELA system **(**Figure 5**)**. It is located along the trunk and lower extremities. What's more, it is a computer-assisted and long term analysis device for the detection of musculoskeletal stress. In this device it was implemented elements such as inclinometers, gyroscopes, digital angle sensors and potentiometers. The analysis of the measurements recorded was based on the ergonomic posture standards ISO 11226.

Figure 5 - Nurse using CUELA system during work-related tasks. (Freitag et al. 2007)

Motion capturing for preventive ergonomic assessment possibilities and challenges for practical application. (Klippert, Fritzsche, Gudehus, & Zick, 2008)

The purpose of this article was to verify the processes, products and resources in a digital factory. Since a lot of tasks in the product assembly factory have to be manually carried or manufactured. Due to the influence of the personnel performance in the productivity and quality of the products and its health, it is important to have an early production planning of the workplace design to avoid further ergonomic problems.

Along the article it is presented different motion capture technologies as a possible solution for reducing the time for programming the movements of digital humans. The technologies presented are: Animazoo Gypsy Gyro 18, CUELA (system used by Freitag et al. 2007) and MeMoMano (for a specific characterization refer to the article Klippert et al. 2008).

It is concluded that the CUELA system is the most elaborated for motion capturing, because it allows the assessment of several different working tasks and environments. Nevertheless, the limitation of CUELA system is the movement liberty constrain that it has. For instance, the potentiometer and structure placed along the legs. On the other hand, MeMoMan system works entirely without sensors or markers, condition that gives completely liberty of motion to the subject. Still, it has problems when the person is occluded from the system. Gypsy Gyro 18 system does not have problems with occlusion. Yet, it is presented magnetic interferences into the system that produce wrong assessments of the data. All in all, these devices let to make a validation of certain assembly activities for a more adequate production planning, but still the continuous assessment of the postures is missing.

Wearable Activity Tracking in Car Manufacturing (PERVASIVE computing, 2008).

In 2008 it was applied a wearable system capable of monitoring upper body activities that support a cars' production or maintenance. Also, the system delivered "just-in-time" information about the activities to be performed by the subject.

The study was done in cooperation with the European car manufacturer Skoda, being able to test the system in real car production conditions. The subjects were asked to perform a series of non-complex and complex activities from construction processes. The most important fact of this investigation is that, the subject performed the same activities with and without real time feedback from the system.

The retrospective of the articles mention above give an important knowledge of the possibilities and problems that have to be solved during the investigation. Trunk postures have an influence in the development of MSDs more than other movements of the body. It has been proved that, the long term prevention of awkward postures is not completely solved. For instance, by training the workers to perform and limit the body to certain movements.

On the other hand, the elements used in the variety of systems have to be carefully selected to avoid magnetic interferences, movement limitations and others mentioned. Also, the identification of the most relevant information has to be improved. So that the signals collection and processing is considerably efficient and not long time consuming.

1.3.7 Feature extraction

Consequently, for the signal processing of the data acquired, it will be made a feature extraction. It will be used a feature selection method, for a posterior classification of the trunk movements.

An important part of signal processing is the feature extraction, which objective is the extraction of additional or relevant information presented in the raw data. In this process, the goal is to investigate which characteristics of the signal can be used to identify in the best accurate way the representation of the reality, in this case, trunk positions, angles or movements. For more information see Chapter 40.

1.3.8 Offline Classification

The classification of the movements and positions data of the trunk will be done by Malahanobis LDA classifier. This classifier is based on the malahanobis distance, taking in to account the variance and correlated features between the different classes. It is obtained a linear discriminant function in the form of hyperplanes which is going to predict the class of the incoming new data (Marques de Sá, 2001).

2. METODOLOGY

2.1 FIRST SPECIFIC OBJECTIVE: PROCESS THE INERTIAL SENSOR SIGNALS FOR THE ACQUISITION OF THE TRUNK MOVEMENTS FOR DETERMINING ITS POSITION.

In the process of assessing the trunk movement, the inertial output signals are going to be recorded in specific and different motions for a further identification of the behavior. The objective of this first stage is to identify the possibilities and limitations that have to take in to account for the next stages. Moreover, it will be detected which changes has to be done to the system accordingly to the advantages of the different manipulation and placement of the sensor on the trunk.

For this manner, it is going to be elaborated an experimental paradigm that can determine the different outcomes of the body movements. These will give better insights, which determine the experiments that will be developed through the investigation. Such as a specific set of movements for the classifier training.

2.2 SECOND SPECIFIC OBJECTIVE: ANALYZE THE SENSOR SIGNALS FOR THE FEATURE SELECTION IN ORDER TO ASSESS WHICH FEATURES PROVIDE MOST OF THE RELEVANT INFORMATION.

After having a better understanding of the inertial sensor signal in the movements studied, the next objective is to extract the most relevant information from the signals for this specific focus as possible. It includes evidence on the flexion and extension, rotation and lateral bending of the trunk. Depending on the characteristics extracted or selected from the data acquired, the feature extraction will be done through the usage of feature selection methods, as for example, Sequential Forward Feature Selection (SFFS). Consequently, it leads to the extraction of signal information that better represents the actual movements of the trunk and excludes irrelevant information (noise). The features of the signals will be the data use to train the classifier to identify the position of the subject as acceptable or not acceptable.

2.3 THIRD SPECIFIC OBJECTIVE: DEVELOP AN OFFLINE CLASSIFICATION OF THE TRUNK MOVEMENTS.

For the offline classification of the trunk movements it is going to be used the Malahanobis LDA (MLDA) classifier. For the training of the MLDA, the assessment of different setups of body movements has to be done. It includes, training with each type of movement alone, or training with a set of combinations of trunk movements types. The training with each type means that, the training set is going to be composed of trails of a class including the flexion of the trunk, other trails of a class with lateral bending and another one with rotation. On the other hand, the training using set of combination stands for, training with trails including two different types of movement, for instance, flexion and rotation of the trunk.

3. DEVELOPMENT OF A SYSTEM FOR THE IDENTIFICATION OF TRUNK MOTION

3.1 INERTIAL MEASUREMENT UNIT (IMU)

System produced by Otto Bock HealthCare GmbH. The IMU used consist of 4 inertial sensors. Each of these is composed of one accelerometer, one gyroscope and one magnetometer. Using this integration of components, it is possible to determine the direction and orientation of the sensor.

This system is connected by Bluetooth to the computer. A program was developed by the company to acquire the system's signals with a sampling rate of 50 Hz.

Because it was going to be used by MatLab, it required to create a communication between the two software. The communication was made by Java, enabling the data acquisition to MatLab. The signals delivered by the inertial system are accelerometers, gyroscopes, magnetometers and quaternions. Quartenions were calculated by the inertial system delivered.

3.2 RAW SIGNAL ANALYSIS

After acquiring the signals, it was studied the behavior of each of them. With this step it was going to be seen the pros and cons of the signals, and with which of them is possible to identify the trunk's position.

An example of accelerometers and quaternions signals is shown in Figure 6 and **Error! Reference source not found.**.

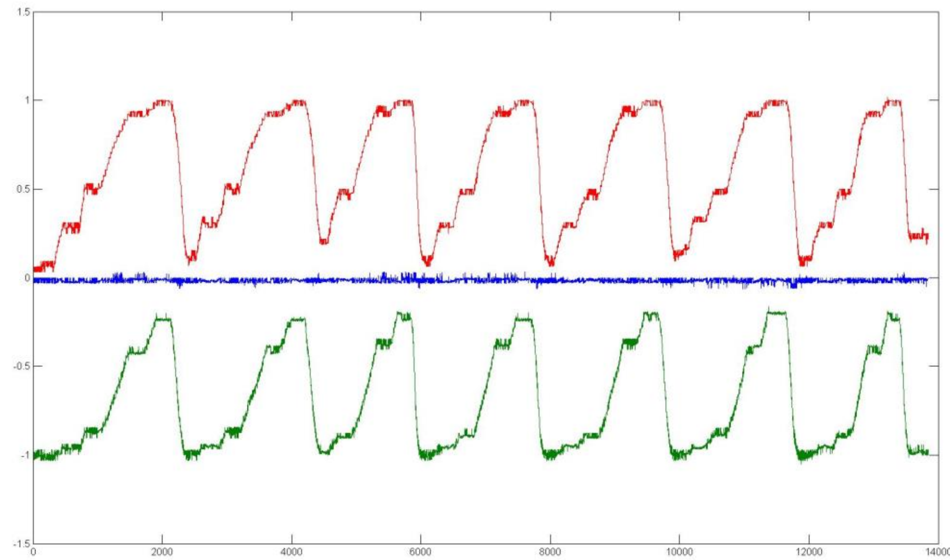


Figure 6: Example of accelerometer data.

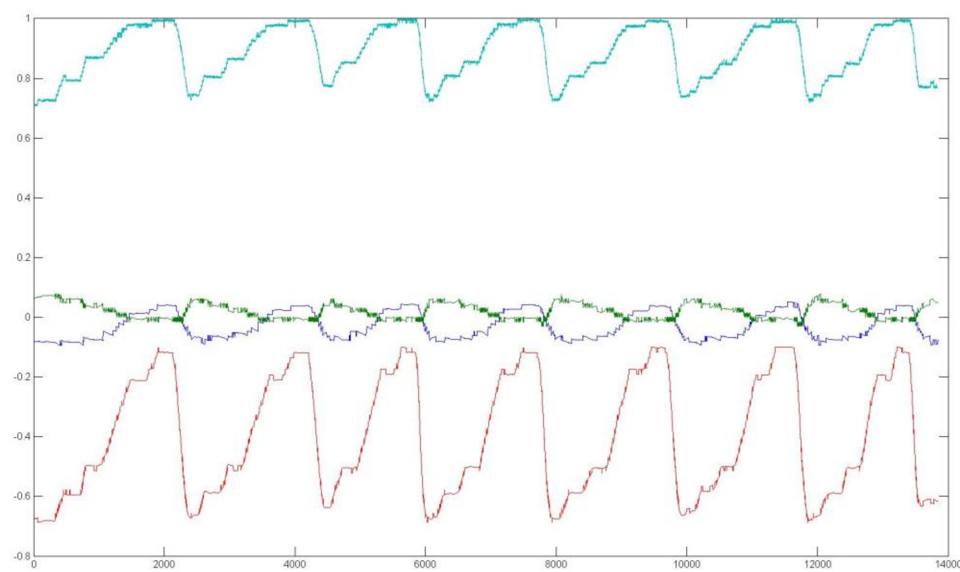


Figure 7: Example of quaternion data.

In figures 6 and 7 the signals are from the same recording where the subject performed seven flexion movements of the trunk. The accelerometer data, Figure 6, is appreciated that there is a clear movement of the trunk, and the signals are stable to be used.

The last signals, the quaternions, Figure 7, are the most stable and representative of the trunk position. Having four signals representing the direction of the sensor.

3.3 SENSOR AND MARKER PLACEMENTS

Without a clear placement of the sensors to get the most accurate trunk angles, it was studied two placements. The first option was all four sensors in the line of the spinal cord. This method was tried by other researchers at the company and it worked well. But still, due to the application that they had was different, it was tried again. The second placement option was to put them on parts of the back close to the markers of Qualisys system. The sensors in these two options were placed on a very tight T-shirt to avoid displacement during the movements.

Markers are placed on the body in specific points depending the movements that it will represent. For this, it was taken in to account the placements of the markers in an optical motion system. For the flexion of the trunk, the markers are placed on the spinal cord, vertebra C7 and L5, which creates a vector. For the rotation of the trunk, they are placed on the shoulder, more specifically on the left and right acromion. To create the vector of rotation, identifying the body position, it is used the vector created by the connection between the markers placed on L5. Having as a rotation of the trunk the difference between the shoulders and the hip. Lateral bending was calculated having the same vector used for flexion and the vector of L5.

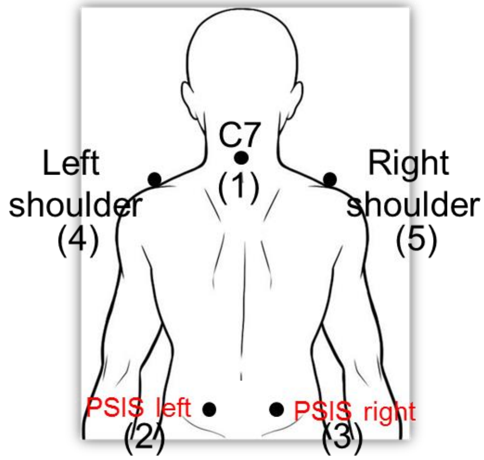


Figure 8 – Placement of the markers.

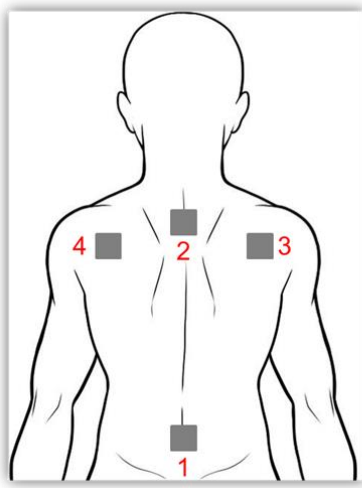


Figure 9: Placement of IMU on the back of the subject. On red is shown the number of the sensor.

On Figure 9, it is shown the placement of the sensors. Sensor 1 was placed on the L5 vertebra to have a reference of the body, more specifically of the movement of the hip. The hip is necessary to calculate the angles of the back.

Sensor 2 was placed near the C7 vertebra, this sensors is going to determine the flexion of the back in relation with sensor 1. Also, this relation is going to give the lateral bending of the subject.

On the other hand, the best representation of the rotation of the subject was made by the relation between sensor 1 and 4.

3.4 ANATOMIC ANGLE CALCULATION USING QUALISYS AND IMU.

It was done a study of the positioning of the sensors on the back. Two of the most important of these possibilities are shown in Figure 11. These position of the sensors let a free movement of the subject and may have the best representation of the anatomic angles compare to the angles calculated based on Qualisys.

The anatomic angles were calculated using the quaternions data of each sensor. The represented movement depended on the related sensors. For example, if the sensor placed close to C7 vertebra and the sensors placed on the L5 vertebra are interpolated, it is possible to get the flexion and lateral bending from it.

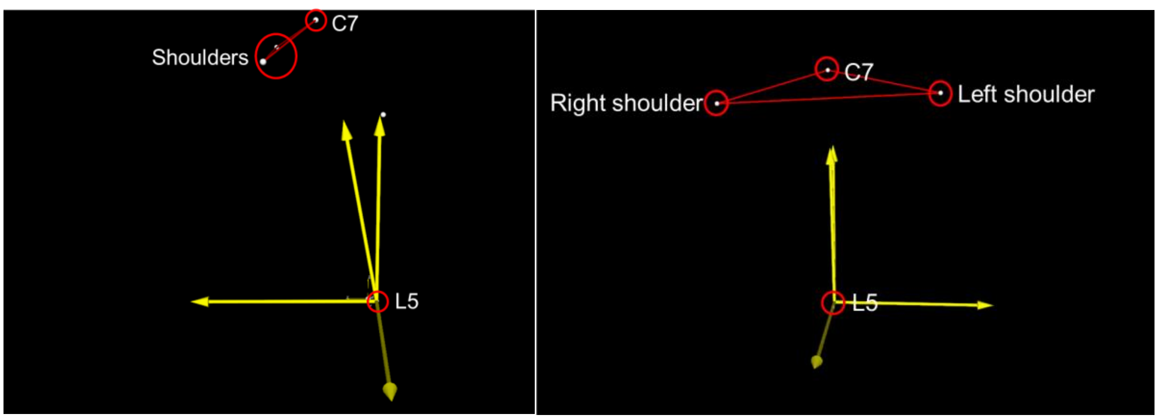
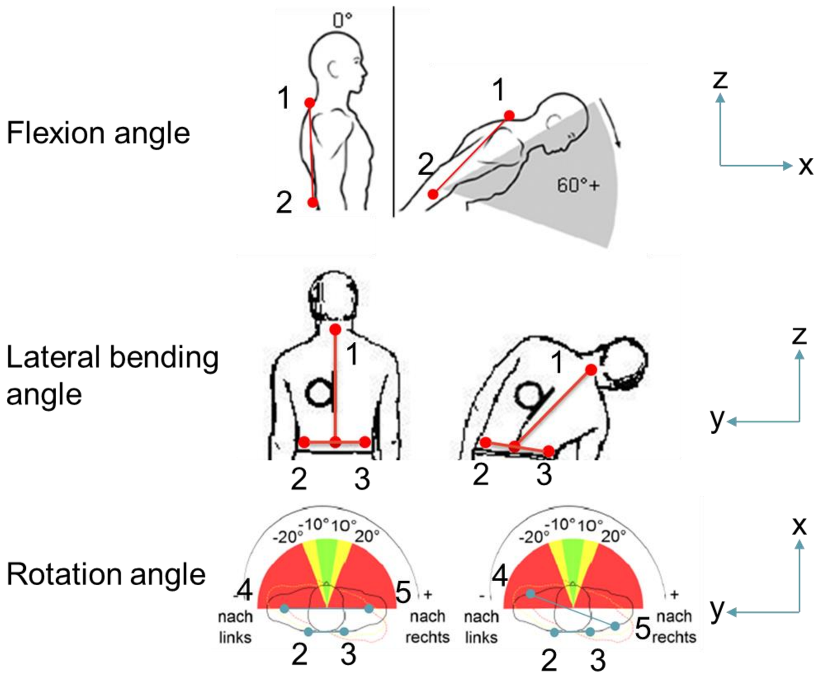


Figure 10: Vector representation of Qualisys system.

The calculation of the angles are going to be graphically represented (see reference numbers of

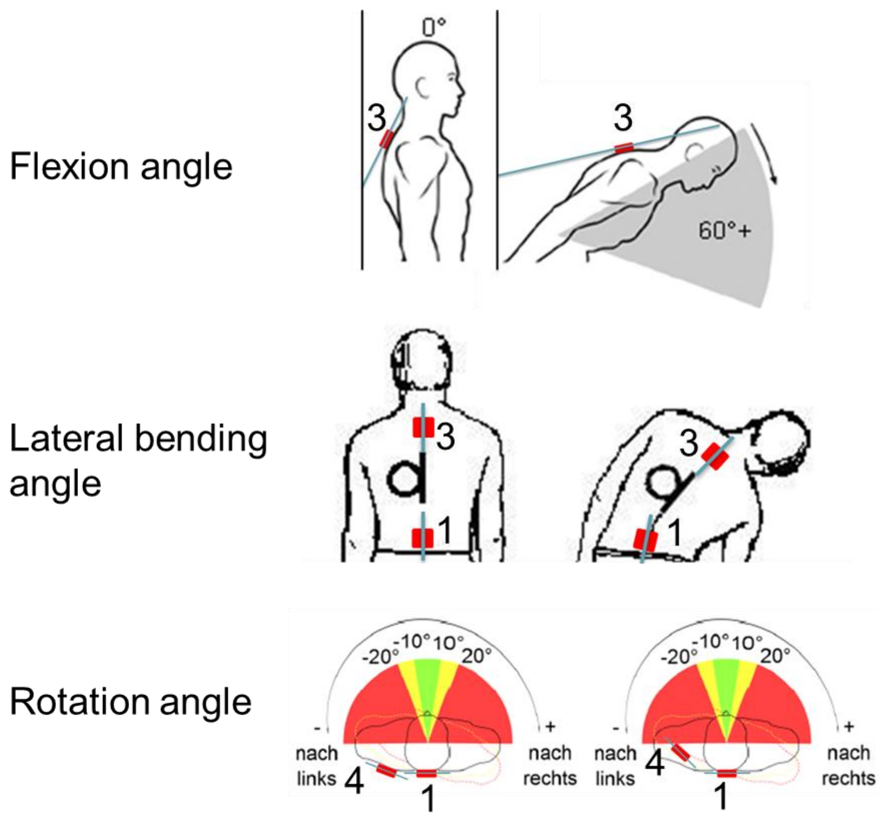
Figure 8 and Figure 9):

Qualisys setup



The anatomic angles calculated from the Qualisys were: Flexion: vector create by PSIS right and left, attached to the marker on L7, having as a reference the global coordinates of the body. Lateral Bending was calculated using the same vector of flexion but its projection on the plane *yz*. Rotation was calculated by using the angle between the vector of the shoulders and the PSIS right and left relative to each other.

Inertial sensors setup



Following, the calculation of the angles using IMU it was required to use the quaternion equations showed in section 1.3.3.

The angles calculation of the IMU were: Flexion: sensor 3 quaternions were converted to Euler angle. Lateral bending: quaternion product of sensor 1 and 3. The resulting quaternion was converted to Euler angle. Rotation: quaternion product of the conjugated sensor 4 and sensor 1. The resulting quaternion was converted to Euler angle.

Equation 4 – IMU angle calculation.

$$Flexion = Quaternion2Euler\ (Q_3)$$
$$Lateral\ Bending = Quaternion2Euler\ (Q_3' * Q_1)$$
$$Rotation = Quaternion2Euler\ (Q_1' * Q_4)$$

3.5 ELABORATION OF FIRST EXPERIMENT.

The first experiment was intended to try sensor placements, calculated angles and other experiment features.

For the assessment of the device performance it was made a first experiment. In which the subject was asked to do recordings on different angles in flexion, lateral bending and rotation (see Figure 11). The subject had to stop from 3 to 5 seconds in the specific angles. For the identification of the angles, it was developed a program that showed and reproduced a sound at the moment of reaching an angle.

The flexion angles were 10, 20, 60 and 70 degrees. In lateral bending and rotation the angles were 10, 20, 30 and 40 degrees.

The calculation of these angles were made using the angles calculated using the IMU. Because, the angles were real-time calculated, shown and used. On the other hand, to use the anatomic angles extracted from the Qualisys system was necessary to create a very complex algorithm and do many changes on the system.

It was done at a Gait for the usage of Qualisys system. This system is considered the gold standard in the body movement measurements. It was used simultaneously with the MatLab program. For the synchronization of the two system, it was necessary to use a trigger signal from the computer to an analog input on the Qualisys system. This channel then was extracted from the system data for the offline synchronization of the two systems signals.

The MatLab program had the trigger send at the moment of starting recording, all in one action to avoid mistakes. Additionally, the program reproduced a beep on any angle or angles. These angles had to be set up before the recording started.

The experiment was like follows:

Flexion Trial:

Started in 0 degrees position, standing, and the reference of the IMU system was recorded. Then the subject was ask to frontal flex the trunk to 20 and stay in that position from 3 to 5 seconds (subjectively). After this time, subject continued flexing to 60, stop from 3 to 5 seconds, and then 70, stop from 3 to 5 seconds, and again go back to starting position. This was considered one repetition. In this experiment it was done 6 repetitions.

Lateral bending trial:

Started in 0 degrees position, standing, and the reference of the IMU system was recorded. Then the subject was ask to bend laterally to the right to 10 and stay in that position from 3 to 5 seconds. After this time, subject continued lateral bending to 20, stop from 3 to 5 seconds, and then 30, stop from 3 to 5 seconds, and then 40, stop from 3 to 5 seconds, again go back to starting position and start lateral bending to the left stopping at the same degrees. Lateral bending to the right and left was considered as one repetition. In this experiment it was done 6 repetitions.

Rotation trial:

Started in 0 degrees position, standing, and the reference of the IMU system was recorded. Then the subject was ask to rotate to the right to 10 and stay in that position from 3 to 5 seconds. After this time, subject continued rotation to 20, stop from 3 to 5 seconds, and then 30, stop from 3 to 5 seconds, and then 40, stop from 3 to 5 seconds, again go back to starting position and start rotating to the left stopping at the same degrees. Rotation to the right and left was considered as one repetition. In this experiment it was done 6 repetitions.

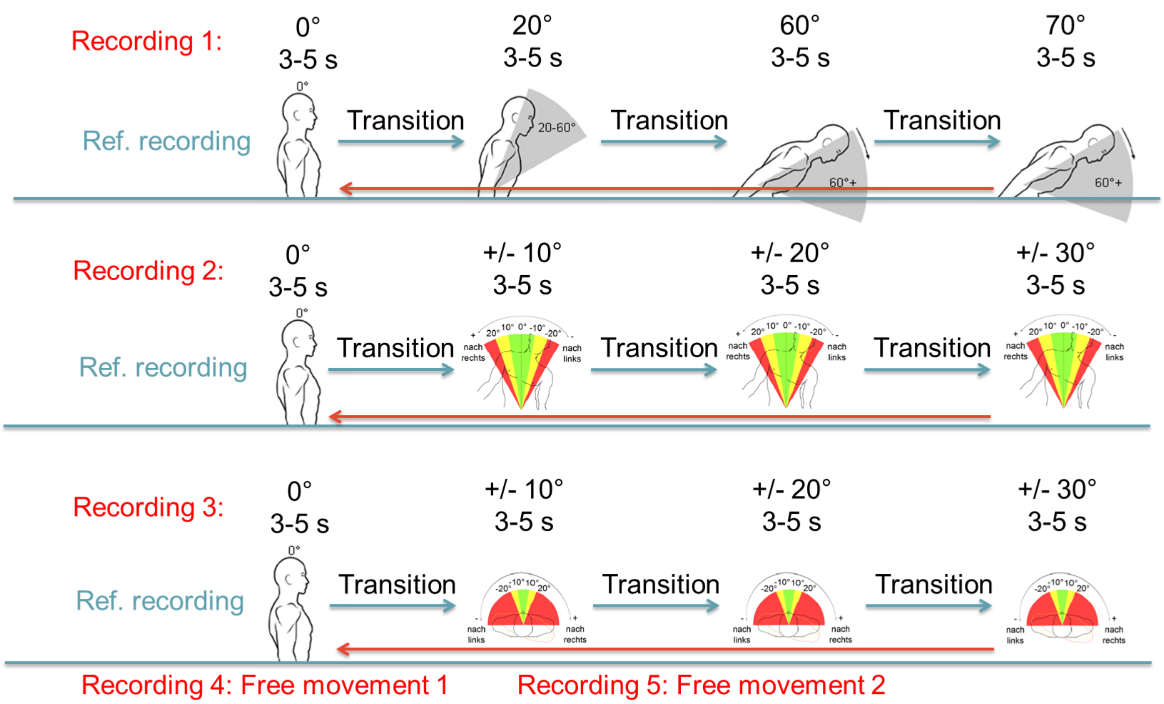


Figure 11: First 3 trails of experiment #1.

Additionally, it was done another recording. It was around 2 minutes of only trunk free movements. Subject was ask to move the trunk freely in any direction and doing some combination of movements. This recording was meant to simulate real life situations, but, as mention before, it was in a static position (no translational movement).

The experiment was done by one subject, due to that it was a try of the systems and program performance.

3.6 SENSORS PLACEMENT ANALYSIS

The analysis of the first experiment gave the conclusion that it was needed that the fixation of the sensors had to change (explanation in Chapter 4).

To find the best fixation, it was done some trials using different materials and methods. In Figure 12 can be seen the problems of the T-Shirt set up. On the left side of the figure it can be seen the distance between the belt of the subject and the sensor 1, nearest the belt, in standing position. On the right side, the subject did a flexion of approximately 40 to 50 degrees and the displacement of the sensor is clear. This first approach was done because an interface based on a T-shirt wants to be made. This way the system is much more user friendly and applicable in many areas.

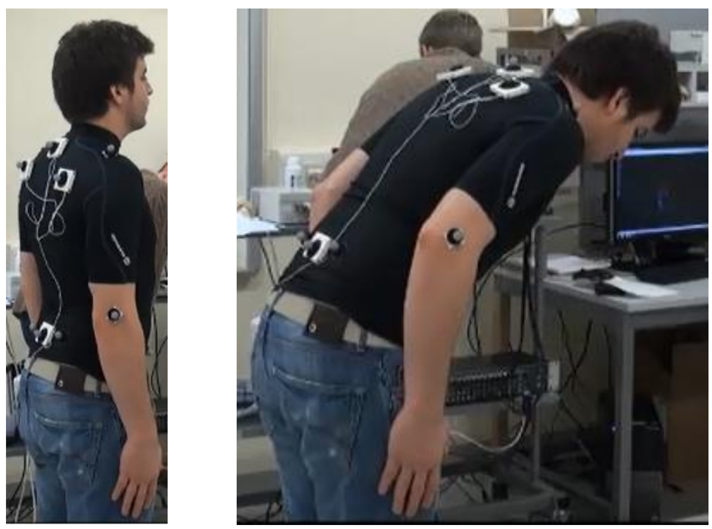


Figure 12: Sensor displacement using T-shirt and velcro fixation.

The most accurate placement of the sensors were using double tape and putting every sensors directly on the skin. With this, the displacement of the sensors were minimum, reducing artifacts in the signals, as shown in Figure 13.

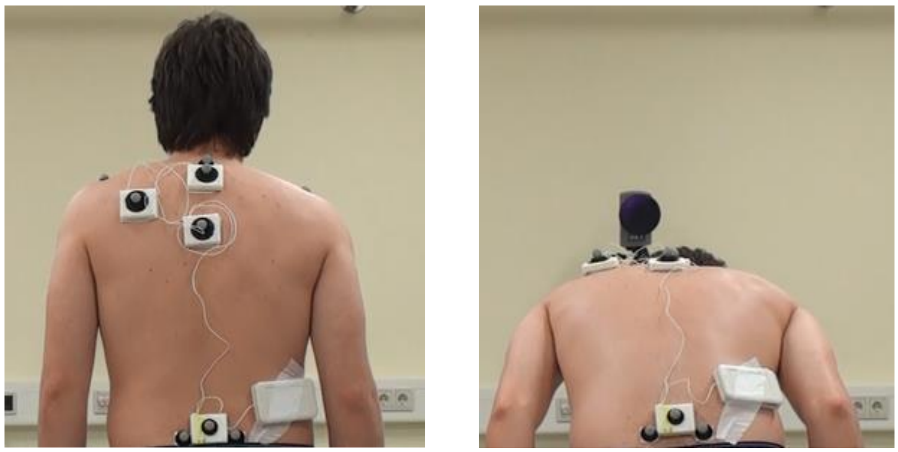


Figure 13: Sensor displacement of double tape fixation.

3.7 CONCLUSIONS OF FIRST EXPERIMENT FOR NEXT STEPS

After the first experiment, analysis and classification of the signals were done. During this process, some of the features of the experiment were changed, improved or deleted. These was done thinking on the improvement of the classification. Also, to understand the relationship and considerations of the program being developed and the gold standard system (Qualisys).

The aspects to change were:

- The angles being measure had to be recorded: in the first experiment the angles were not recording and at the moment of doing the analysis of the angles, they had to be recalculated and it was not certain that those were the angles measured at the time of the experiment.

- IMU placement and fixation had to be improved: as explained in Chapter 3.6, the signal were influence of artifacts that were coming mostly from the fixation of the sensors.

- Video recording of the experiment from the back of the subject: the video gave us a way to have a better analysis of the movements in correlation with the signals. It can be seen sensor movement and other features affecting the signals.

3.8 EXPERIMENT #2 EXPLANATION

In the second and final experiment it was done flexion, lateral bending and rotation trial mentioned in experiment #1. However, it was done 3 repetitions of each movement. Also, subject was ask to do static free movement.

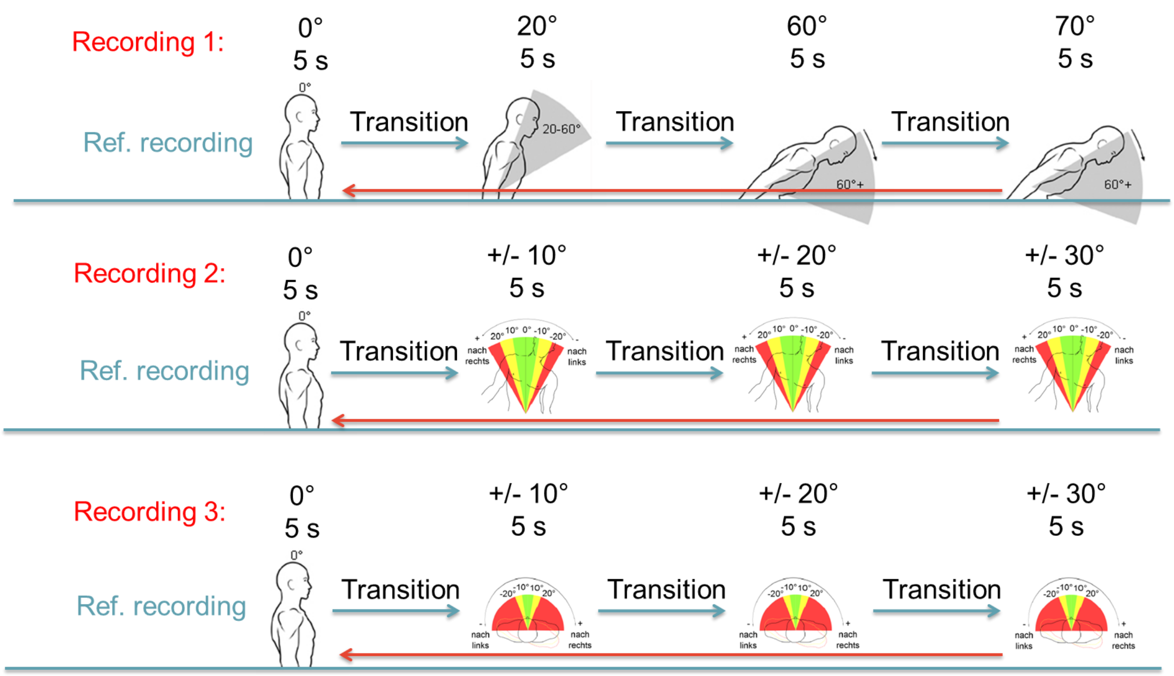


Figure 14: First 3 trials of experiment # 2

The difference between the two experiments was that the time on each specific angle was timed using the program developed. With this, the recording were more precise and we avoided the subjective time from the subject.

In static free movement, as in experiment #1, the subject was ask to move only the back freely, staying in the same position. It was done one recording. An example in Figure 15.

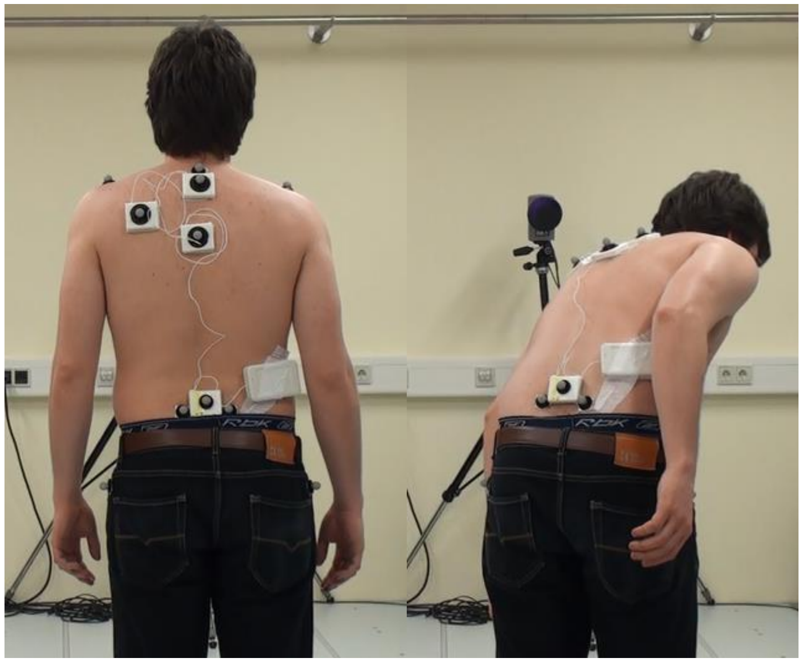


Figure 15: Images of Static free movement

Additionally, there was a 5th trail was the subject had to do dynamic movement. This means, the subject had to walk in circles in an area of 2m x 1,5m, approximately, doing free back movements (Figure 16). This trail was done to simulate real life movement conditions. This area was mostly limited by Qualisys system, but the IMU was able to cover a much bigger area thanks to the wireless connection.

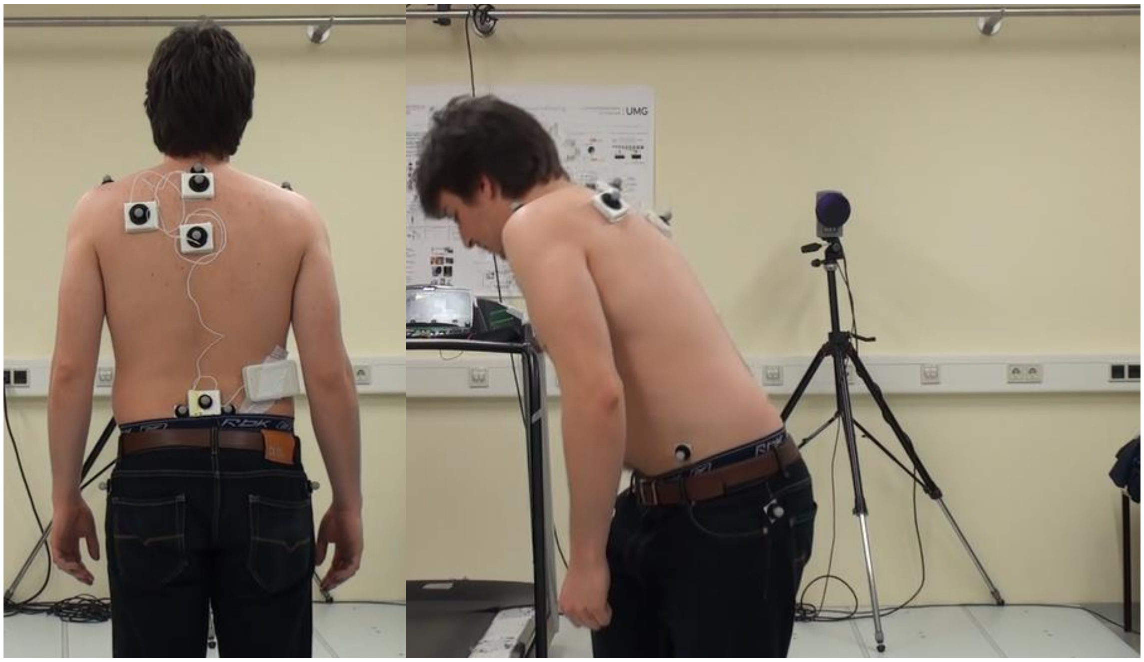


Figure 16: Images of Dynamic free movement

For this experiment, every trail were video recorded to make an analysis of the movements and sensors displacement. Moreover, the angles were recorded to compare to the offline calculations and the calculated angles made by Qualisys system.

3.9 FEATURE EXTRACTION

After acquiring the signals of every trail it is important to extract the most relevant and significant information. It has been created a list of features that have the possibilities to identify this information. This list has been done using features implemented on articles and other literature.

The selected features for the feature selection method were:

- RMS (Root mean square)
- MAV (Mean absolute value)
- logVAR (log. of the variance)
- WL (Wavelength)

- INT (signal intergral)
- Kurtosis
- SSC (Slope sign changes)

3.10 FEATURE SELECTION

The features written above are not all useful to represent the information needed to classify each movement. Because of this, it has been used a feature selection method, which finds a subset of features that give no redundancy and most relevant information, causing the best classification accuracy.

The feature selection method used was Sequential Flouting Feature Selection (SFFS).

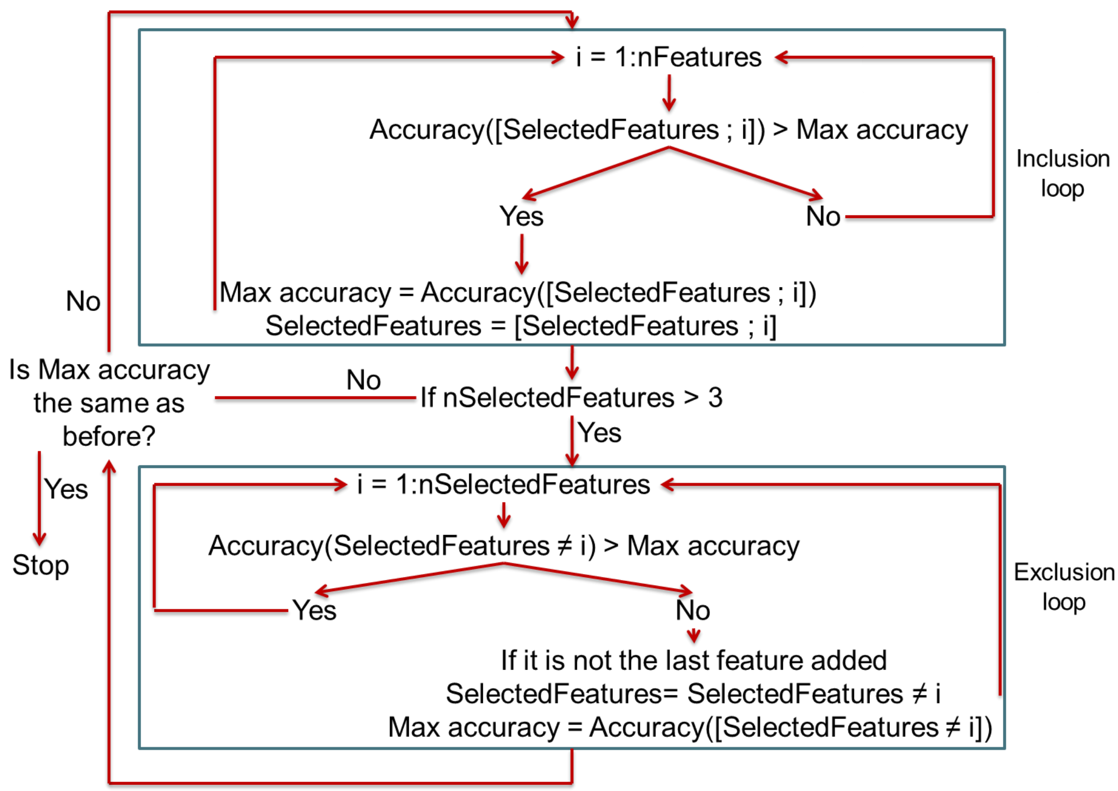


Figure 17: Sequential Flouting Feature Selection explanation.

SFFS method was selected to be the best for this application because of the inclusion and exclusion characteristic. In the inclusion of the features, the method finds the group of features that give the best accuracy of classification. However, after including more than two features, it comes the exclusion, when the method take a group of the features selected (excluding one) and finds the best sub set of the group of features initially selected to be the most accurate one and eliminates a feature (Figure 17).

3.11 CLASSIFICATION EXPLANATION

In the process of classification, it was used Linear Discrimination Analysis (LDA) classifier. For the classification of flexion, lateral bending and rotation, it was necessary to use three different classifications, each one with two classes. This means, use one LDA to classify class 1 and 2. Class 1 being all data were flexion was more than 10 degrees, no matter if there is or is not lateral bending or rotation, and class 2 was when flexion was less than 10 degrees. For the second classifier class 1 was all data were lateral bending was more than 10 degrees and class 2 were lateral bending was less than 10 degrees. Third classifier was for identifying rotation, using same type of classes as flexion and lateral bending.

The angles used to create the classes were the anatomic angles calculated by using Qualysis system data.

As a graphical example see Figure 18 (training data):

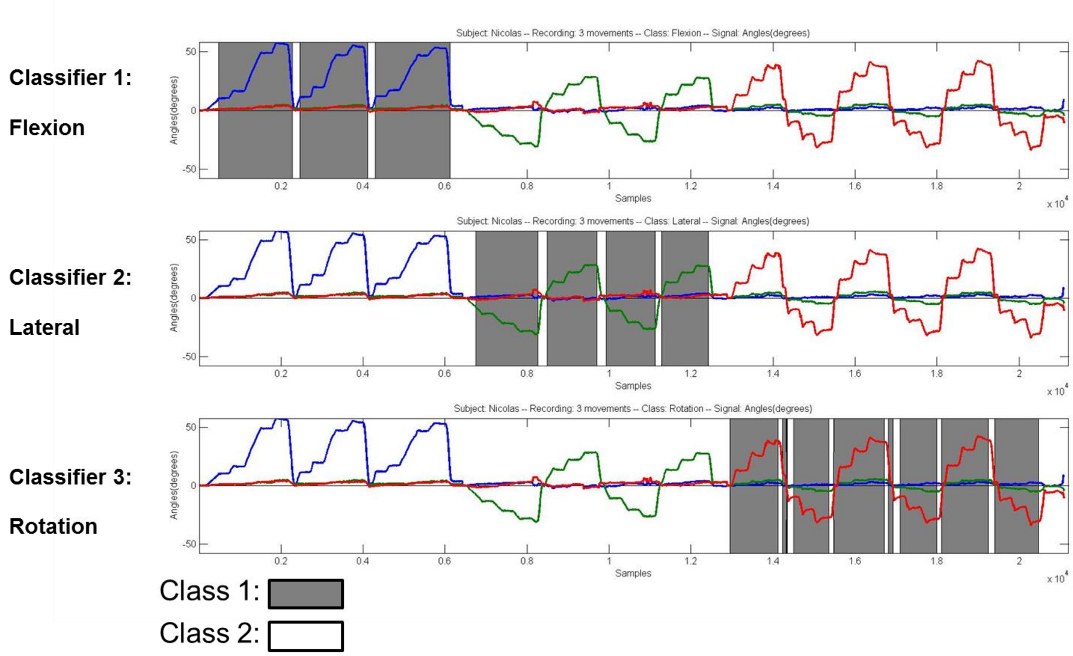


Figure 18: Classifiers with a graphical representation of the classes.

The data for classification was the quaternion product of sensor 1 (placed at L5) and sensor 3 (placed at C7). Here sensor 1 is working as a movement reference, no matter if the subject walk or change the position of the body, sensor 3 is going to be based on the position of sensor 1, example Figure 19.

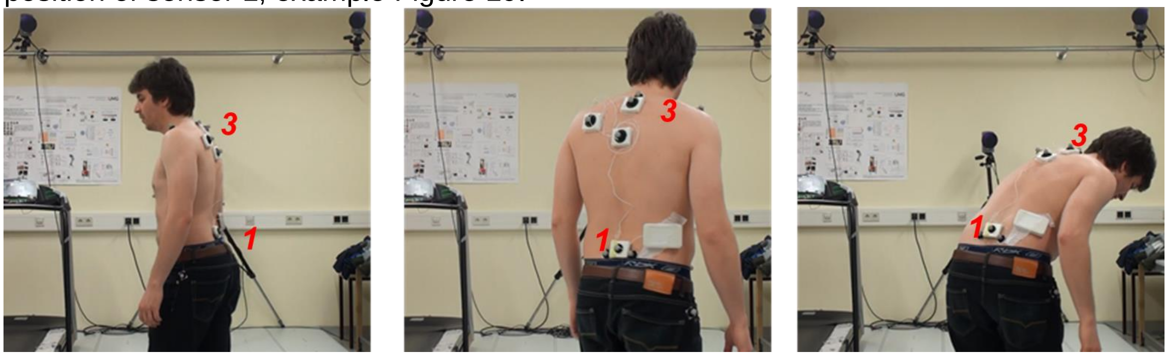


Figure 19 - Dynamic movement showing sensor 1 and 3 in different spatial positions.

The gyroscopes and magnetometers are not use in the classification. Gyroscopes are unstable for a long term usage and they have short and long term baseline drift.

The magnetometers signal were not possible to be correctly acquired, so it could not be used. Besides that, the magnetometers are based on magnetic fields, and this would limit the system to work only in no-magnetic areas.

4. DISCUSION OF THE RESULTS

4.1 RESULTS OF THE PROGRAM

In the development of the program it was acquired the four signals, but having some problems with the communication. For the gyroscope and the magnetometers the signals were corrupted, having some jumps and post-processing requirements. However, there is no need of gyroscopes and magnetometers. These two signals had problems of instability mention before in this report.

On the first phase of the project the goal was to detect the back movements, which include flexion, rotation and lateral bending, and the combination of them. Moreover, it was intended to assess the inertial sensors system, the signal processing, compared to a motion capture system.

The comparison between the angles calculated using the IMU and Qualisys system was because the data collected during the experiment is based on the angles calculated by the IMU, for this reason the difference had to be minimum.

The intension on the experiment was to place the inertial sensors and the markers on a very tight T-Shirt, using Velcro to fix the sensors to the body. However, the T-Shirt and Velcro were making the sensors move in different directions and also made displacements of them.

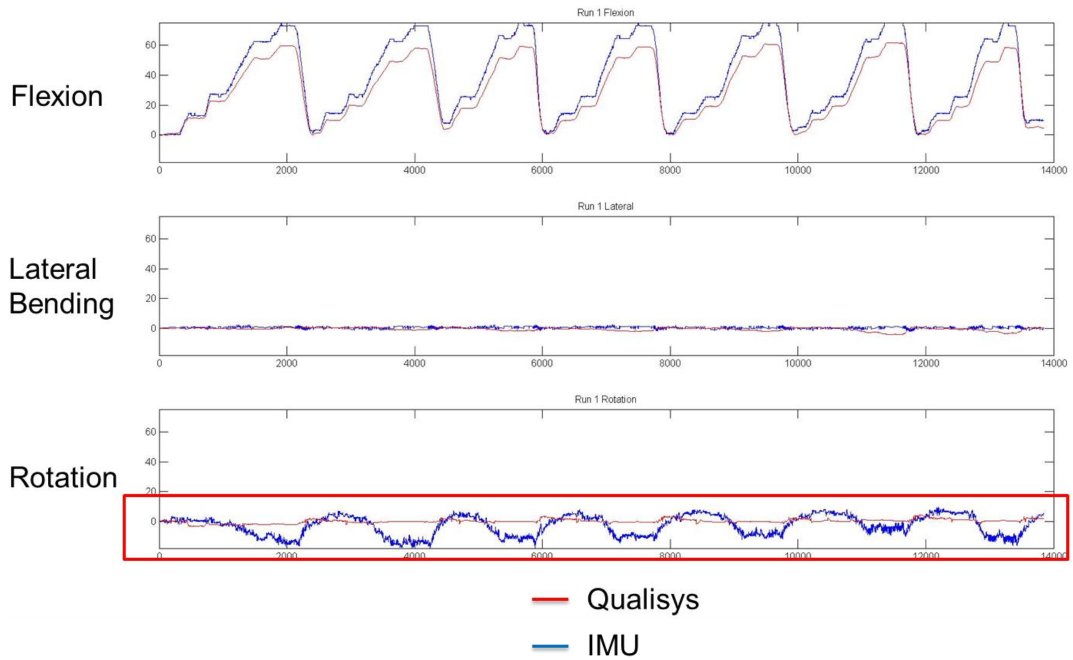


Figure 20: Flexion trial, experiment 1.

At first, the comparison of the flexion angles of the two systems had a very clear difference. As it can be seen on Figure 20, as higher is the angle higher is the difference between the angles. This means that there is a relationship between the two signals.

In the figure above it can be seen the rotation angle (red square) were considerably different compared to the Qualisys system. This was causes by the displacement and movements of the T-Shirt and Velcro.

Then, in the lateral bending (Figure 21) and rotation trials (Figure 22), the results of the angles had less difference, but still had to be minimized.

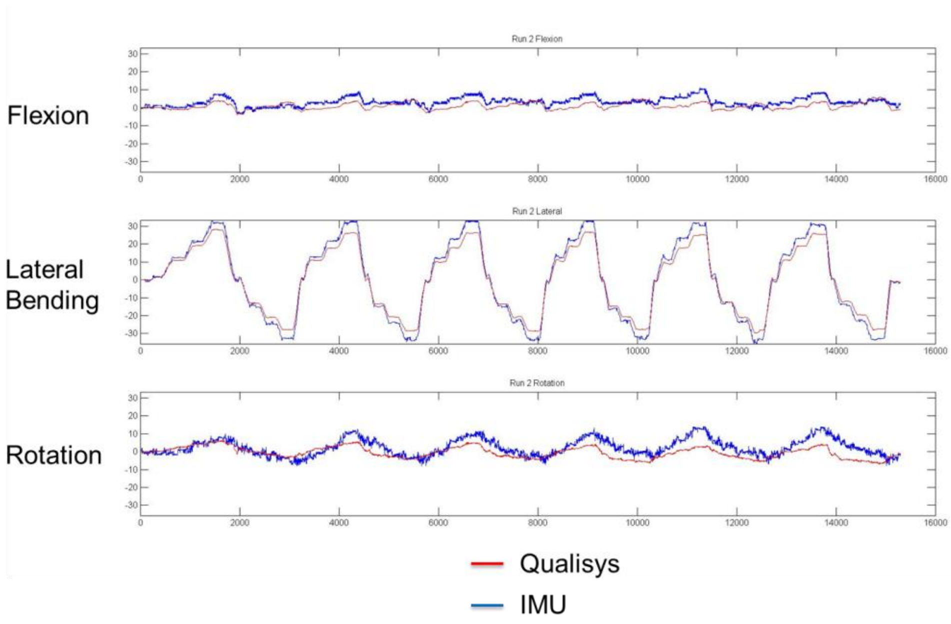


Figure 21: Lateral bending trial, experiment 1.

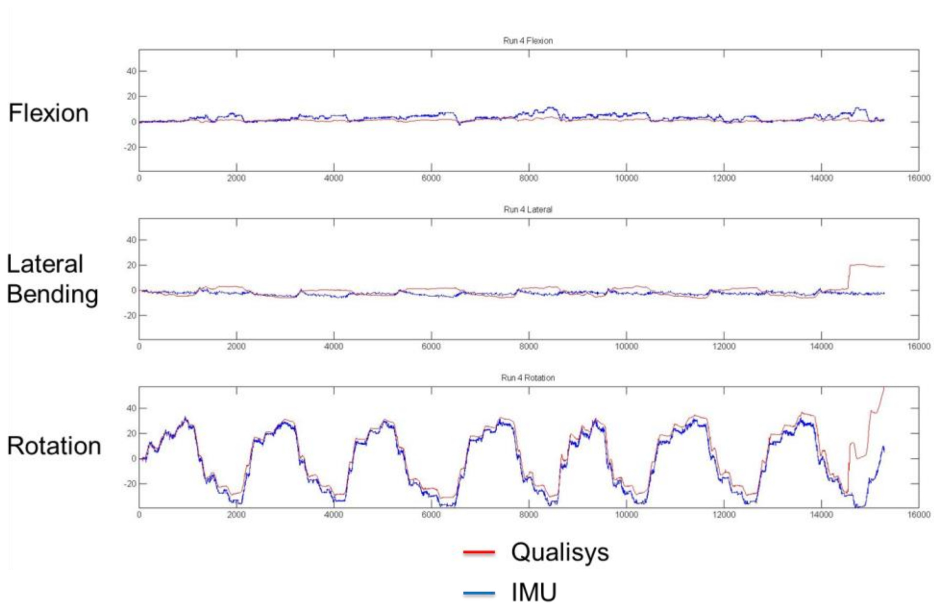


Figure 22: Rotation trial, experiment 1.

At last, the static free movement trial was the test of the program. During this trial, it is important to remember that the subject was asked to move the trunk freely, trying to perform combination of all or some types of movements including all degrees of freedom and its combinations.

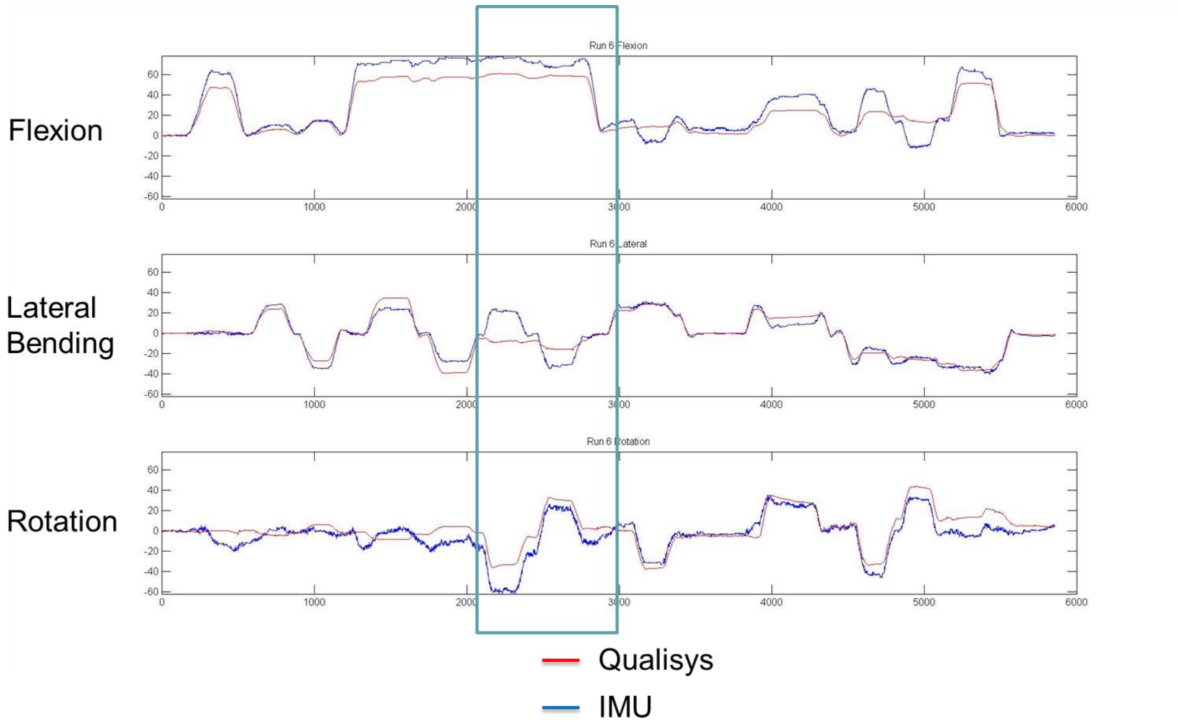


Figure 23: Static free movement, experiment #1.

In the marked part of Figure 23, the subject was doing around 50 degrees of flexion, no lateral bending and two rotations of 40 degrees to each side. But, the angles calculated by the IMU program were not accurate in identifying the difference in lateral bending and rotation. This issue had to be solved to continue with the second experiment.

Looking for a solution of the T-shirt and Velcro used in the first experiment, it was tried to think of a reliable and fast ideas to be applied. At first, it was thought that securing the shirt on the body was going to solve it, but it did not, still there were displacement of the sensors. Then, it was tried to tape the sensors on the body, like in figure #. This fixing came with some problems. One was that the tape stick off the skin, and second the tape limited no movement of the subject because of the tape pulling the skin.

As a third try, it was suggested to use double tape. Double tape was strong enough to stick the sensor to the body and without limiting the person during the movements.

For the next experiment, it was important to video record the subject from the back. Because an analysis of the movements of the body and the sensors can be done. Also, the movements of the sensors and the markers can be compared.

On the other hand, the MatLab program was improved to identify more accurately the angles of every movement. Then, to have a specific stop time in the specific angles, a beep was put after 5 seconds after reaching the angle. Also the angle recording was implemented.

4.2 SECOND EXPERIMENT RESULTS

The results of the second experiment improved. It can be seen in the next

Figure 24.

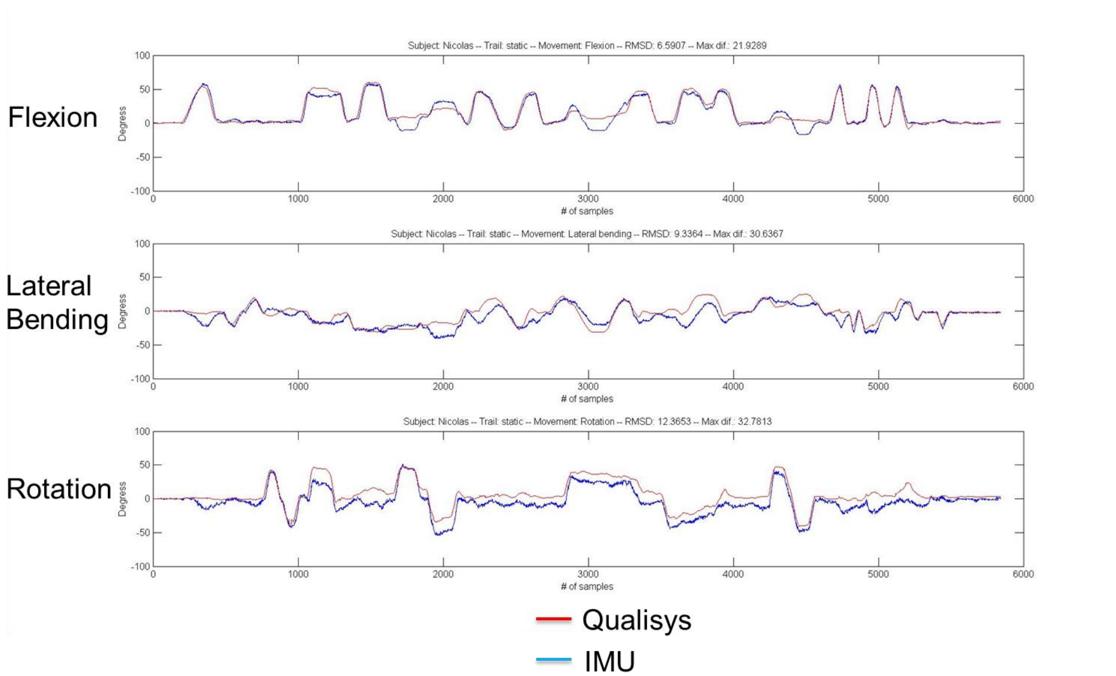


Figure 24: Angles of Static free movement, experiment 2.

After having the close results of the angles of the two systems, the next phase was to use the data recoded in this experiment to classify the movements, but to extract the most relevant information from this data, it was necessary to do a feature extraction and selection.

The results from the feature extraction and selection, as mentioned before, was that RMS (Root Mean Square) and logVar (logarithm of the variance) were the most significant feature of the signals.

In the classification stage, the angles used to separate the classes were the angles from the Qualisys system.

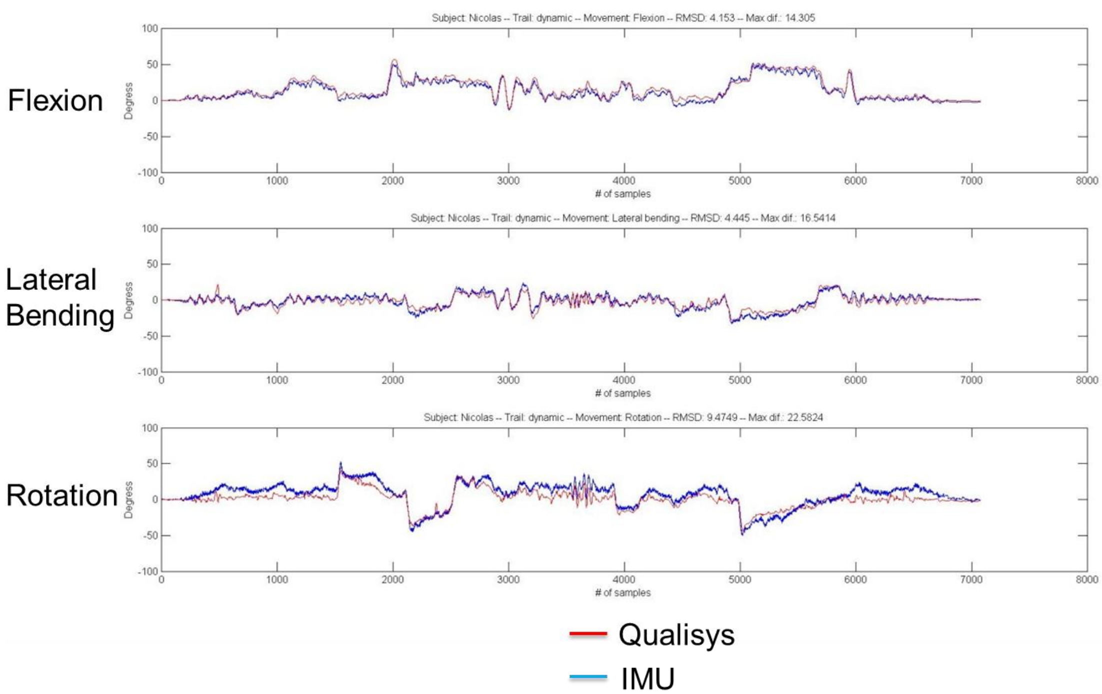


Figure 25: Angles of Dynamic free movement, experiment 2.

It is going to be shown the results of the classification of the three subjects. As training, each one has flexion, lateral bending and rotation trials. As test there is all trials. The first three tests are to analyze the classification results training and testing with the same data. On the other hand, static and dynamic free movements were the most relevant results for a real application.

a)

TRAIN	TEST	SENSORS	MIN ANGLE	ACCURACY (%)			Features
				FLEXION	LATERAL	ROTATION	
Flexion, Lateral, Rotation	Flexion	1* x 3 / 1A / 2A / 3A / 4A	10	96,43	100	100	RMS - logVAR
	Lateral	1* x 3 / 1A / 2A / 3A / 4A	10	100	95,17	99,49	RMS - logVAR
	Rotation	1* x 3 / 1A / 2A / 3A / 4A	10	100	100	91,64	RMS - logVAR
	Static	1* x 3 / 1A / 2A / 3A / 4A	10	95,27	80,13	66,44	RMS - logVAR
	Dynamic	1* x 3 / 1A / 2A / 3A / 4A	10	93,38	81,77	68,54	RMS - logVAR

b)

TRAIN	TEST	SENSORS' SIGNALS	MIN ANGLE	ACCURACY (%)			Features
				FLEXION	LATERAL	ROTATION	
Flexion, Lateral, Rotation	Flexion	1* x 3 / 1A / 2A / 3A / 4A	10	96,67	100	99,84	RMS - logVAR
	Lateral	1* x 3 / 1A / 2A / 3A / 4A	10	100	96,25	99,25	RMS - logVAR
	Rotation	1* x 3 / 1A / 2A / 3A / 4A	10	100	100	86,15	RMS - logVAR
	Static	1* x 3 / 1A / 2A / 3A / 4A	10	91,25	81,47	49,74	RMS - logVAR
	Dynamic	1* x 3 / 1A / 2A / 3A / 4A	10	85,29	55,32	64,98	RMS - logVAR

c)

TRAIN	TEST	SENSORS	MIN ANGLE	ACCURACY (%)			Features
				FLEXION	LATERAL	ROTATION	
Flexion, Lateral, Rotation	Flexion	1* x 3 / 1A / 2A / 3A / 4A	10	96,15	97,63	98,07	RMS - logVAR
	Lateral	1* x 3 / 1A / 2A / 3A / 4A	10	98,52	98,08	98,52	RMS - logVAR
	Rotation	1* x 3 / 1A / 2A / 3A / 4A	10	100	100	84,87	RMS - logVAR
	Static	1* x 3 / 1A / 2A / 3A / 4A	10	84,24	74,1	67,08	RMS - logVAR
	Dynamic	1* x 3 / 1A / 2A / 3A / 4A	10	69,31	80,68	73,98	RMS - logVAR

Figure 26: Classification results a) Subject 1, b) Subject 2, c) Subject 3.

From the fifth to the seventh column it is shown Flexion, Lateral and Rotation, which means classifier 1, 2 and 3 respectively.

The results showed that the investigation of features to improve the classification has to be improved.

In this matter, the calculated angles of the IMU were not used to identify the back motions because is a method with considerable use of memory. Additionally, it does not help for the classification of certain postures that want to be identify, taking in to account the Euler angle singularities that can be presented. Also, the addition of more sensors for the angles to be more accurate would need much more memory consumption of the system.

On the other hand, the investigation of the classification of the back movements can be continued. It can be investigated mainly other feature extraction. The advantage with the classification is that for the future it is possible to identify not only motions, but postures, actions, procedures, among other applications.

Moreover, compering the inertial and motion capture systems, the IMU is closely accurate to the outcomes of the Qualisys. The IMU gives the user more freedom and a wider range of movement. Also, there are calculation that were more complex to do using Qualisys, such as the angle calculation, in which with the IMU system was easier and faster to accomplish.

5. CONCLUSIONS AND FINAL CONSIDERATIONS

The classification of the trunk motion was possible but still with a low accuracy. The advantages of using classification is that there is no singularities as using Euler angles and the program would be more robust and stable, also is easier to add more information or sensors. However, the classifier needs to be trained with specific movements.

On the other hand, the angles calculation seems to be a more accurate way to identify the trunk movements, for the moment. Using this method, there is no need of training, just a reference in standing position. But, the use of Euler angles can generate problems of its singularities and interpretation to anatomic angles. The addition of new sensors or other type of data would increase the computational complexity.

The IMU system classification results, in comparison to the motion capture system, is that using the classifier needs parts to improve and do research. Like, to expand the features to extract from the signal, or use the angles calculated, using the quaternions, as features.

An advantage of the IMU system is that, it is considerably much more portable than the motion capture system. With this system, people have the opportunity to acquire data in the direct place of action and with an easier interface. It means that, as an example, if the subject wants to get data climbing with the IMU system is possible. But, using a motion system would be difficult and time consuming.

During the elaboration of experiment 2, an important limitation of the motion capture system was found. It was the limited area of movement of the subject, and also how problematic it can be that a marker is blocked from a camera. Those problems were completely out of the picture using IMU systems, where only the limitation can be driven by the distance of the wireless connection. Additionally, the tape used on this experiment showed the best results because it avoids the movement of the sensors, which in the future it has to be taken in to account for the application on any clothing.

6. REFERENCES

Altun, K., Barshan, B., & Tuncel, O. (2010). Comparative study on classifying human activities with miniature inertial and magnetic sensors. *Pattern Recognition, Department of Electrical and Electronics Engineering, Bilkent University, Bilkent,*, 3605-3620.

Avci, A., Bosch, S., Marin-Perianu, M., Matin-Perianu, R., & Havinga, P. (2010). Activity Recognition Using Inertial Sensing for Healthcare, Wellbeing and Sports Applications: A Survey. *University of Twente*.

Barbour, N., & Schmidt, G. (2001). Inertial Sensor Technology Trends. *IEEE Sensors Journal*, 332-339.

Boyle, M., Edwards, C., & Greenberg, S. (2000). Th effects of filtered video on awareness and privacy. *ACM*, 1-10.

Diebe, J. (2006). *Representing Attitude: Euler Angles, Unit Quaternions, and Rotation Vectors.* Stanford, California: Stanford University.

EBVElectronik. (2015). Obtenido de http://www.ebv.com/products/product-details/9235/

Freitag, S., Ellegast, R., Dulon, M., & Nienhaus, A. (2007). Quantitative Measurement of Stressful Trunk Postures in Nursing Professions. *Published by Oxford University Press*, 385-395.

Gavrila, D. M. (1999). The visual analysis of human movement: A survey. *Computer Vision and Image Understanding*, 82-98.

Gowing, M., Ahmadi, A., Destelle, F., Monaghan, D. S., O'Connor, N. E., & Moran, K. (2014). Kinect vs. Low-cost Inertial Sensing for Gesture Recognition. Ireland.

Groÿekatthöfer, K., & Yoon, D. Z. (2012). Introduction into quaternions for spacecraft attitude representation. *Technical University of Berlin*. Belin, Germany.

Health and Safety Authority; Health and Safety Executive for Northern Ireland. (2013). Guidance on the Prevention and Management of Musculoskeletal Disorders (MSDs) in the Workplace.

Hong, X., Nugent, C., Mulvenna, M., & McClean, S. (2009). Evidential fusion of sensor data for activity recognition in smart homes. *PMC*, 236-252.

Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung. (2013). Bewertung physischer Belastungen gemäß BGI/GUV-I 7011 (Anhang 3). *IFA*, 1-10.

Klippert, J., Fritzsche, L., Gudehus, T., & Zick, J. (2008). Motion Capturing for Preventive Ergonomic Assessent Possibilities and Challenges for Practical Application. *Produckt- und Produktions-Ergonomie*, 891-894.

Marques de Sá, J. P. (2001). *Pattern Recognition: Concepts, Methods and Applications.* Germany: Springer Science & Business Media.

Mayagoitia, R. E., Nene, A. V., & Veltink, P. H. (2002). Accelerometer and rate gyroscope measurement of kinematics: an inexpensive alternative to optical motion analysis systems. *Journal of Biomechanics*, 537-542.

Min, F., Hu, Q., & Zhu, W. (2012). Feature selection with test cost constraint.

National Institute for Occupational Safety and Health. (1997). Musculoskeletal Disorders and Workplace Factors. *U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES*.

Nicola, P. (2012). EXPERIMENTAL VALIDATION OF XSENS INERTIAL SENSORS DURING CLINICAL AND SPORT MOTION CAPTURE APPLICATIONS. Italy.

Pentland, A. (2000). Looking at people: Sensing for ubiquitous and weareble computing. *IEEE*, 107-119.

PERVASIVE computing. (2008). Wearable Activity tracking in Car Manufacturing. *IEEE CS*.

Qualisys. (2013). *Qualysis*. Obtenido de Qualysis: http://www.qualisys.com/

Qualisys. (s.f.). *Qualisys*. Recuperado el 2015, de http://www.qualisys.com

Reiss, A., Hendeby, G., Bleser, G., & Stricker, D. (2010). Activity Recognition Using Biomechanical Model Based Pose Estimation. *Springer*, 42-55.

Ugulino, W., Cardador, D., Vega, K., Velloso, E., Milidiú, R., & Fuks, H. (2012). Wearable Computing: Accelerometers' Data Classification of Body Postures and Movements. *Springer*, 52-61.

Zhoua, H., Stoneb, T., Huc, H., & Harrisb, N. (2006). Use of multiple wearable inertial sensors in upper limb motion tracking. *Medical Engineering & Physics*. ELSEVIER.

Zinnen, A., ChristianWojek, & Schiele, B. (2009). Multi Activity Recognition Based on Bodymodel-Derived Primitives. *Springer-Verlag Berlin Heidelberg 2009*, 1-18.

ANEXO 1