1. What is EPTS?

1.1 Electronic performance & tracking systems (EPTS)

On one hand, it has been observed an incredible development of technology applied to sports in the last years. On the other hand, it has been proven that the relation between the workloads of the athletes, the injury index and the sport performance is evident, which makes the athlete monitoring an indispensable common practice in the high performance area, sports medicine and sports science in general.

Due to the necessity of monitoring the players and knowing exactly the efforts that they make in training or competition sessions, along with the great evolution that has been experienced by technology, a range of tools has been developed which allows knowing the player performance. These tools are devices known as EPTS.

In this unit, these EPTS devices will be addressed, it will be explained what they are exactly, what types exist in the market, what elements compose them and, lastly, the evolution of regulations for their use in professional football.

Definition of EPTS

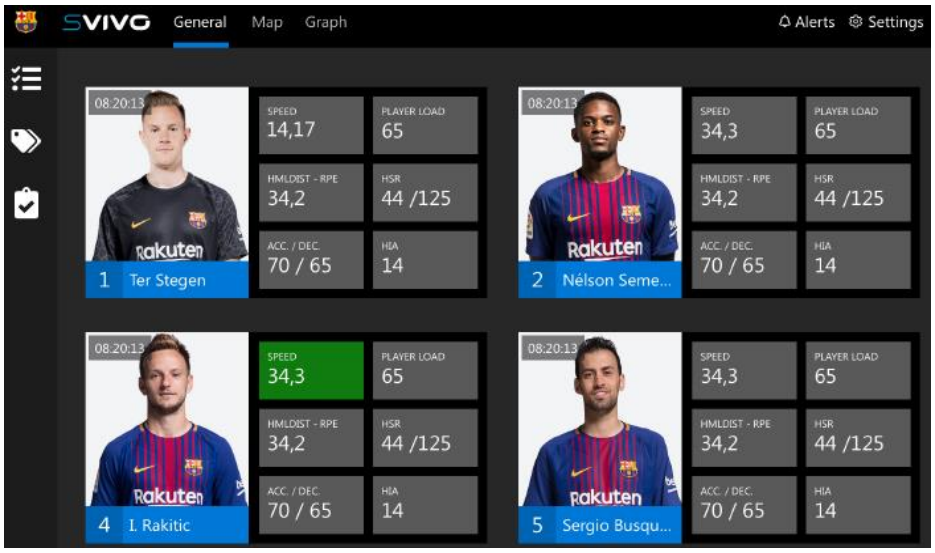
The acronym EPTS stands for **electronic performance & tracking systems**. These **systems** allow the register and the analysis of the data about player performance. Throughout time, numerous terms have been used to refer to these **systems**. Nowadays, and in accordance with the football's governing body, FIFA (2015a), when we talk about EPTS we make reference to:

> Technology used to monitor and improve player and team performance on the playing field. These systems primarily keep track of the players' positions and the ball although they can also be used in combination with microelectromechanical elements (accelerometers, gyroscopes, etc.) in addition to other devices which measure physiological parameters (https://football-technology.fifa.com/en/media-tiles/epts-1/)

Furthermore, EPTS allow real-time analysis which enable all the team members (coaches, physical trainers, doctors, among others) to have valid data and immediate feedback on what happens on the playing field. In this way, they are able to make quick decisions based on the metrics they observe. That is to say that any member of the team can display at any time (whether it be at the training session or at a match) the speed at which the

players are running, the accumulated high-intensity distance, among other variables (figure 1).

Figure 1: Data display screen in real time.



Source: Own elaboration based on SVIVO software (Real Track System S.L., 2019).

EPTS devices not only provide data to do a physical exam of the player but also offer tactical data and information. Such information allows establishing relations, like distances or areas between players, as well as heat maps (figure 2).

Heat maps also provide a great deal of information. These devices allow trainers to see all this information in real time and to make decisions on the spot.

Figure 2: Heat map display screen in real time.

Source: Own elaboration based on SVIVO software (Real Track System S.L., 2019).

Last but not least, with EPTS devices, raw data of the signals from the different sensor can be analysed. When we talk about raw data of the signals we make reference to the volume of data that has no treatment and that comes from the different sensors of the

device: GNNS, accelerometers, gyroscopes, magnetometer, and barometer, among others. These sensors allow the user to perform the analysis that best suits their needs.

Classification of EPTS devices

There are different types of EPTS devices. Figure 3 shows the different technologies that are used in the sports performance world.

Figure 3: Classification of EPTS devices.

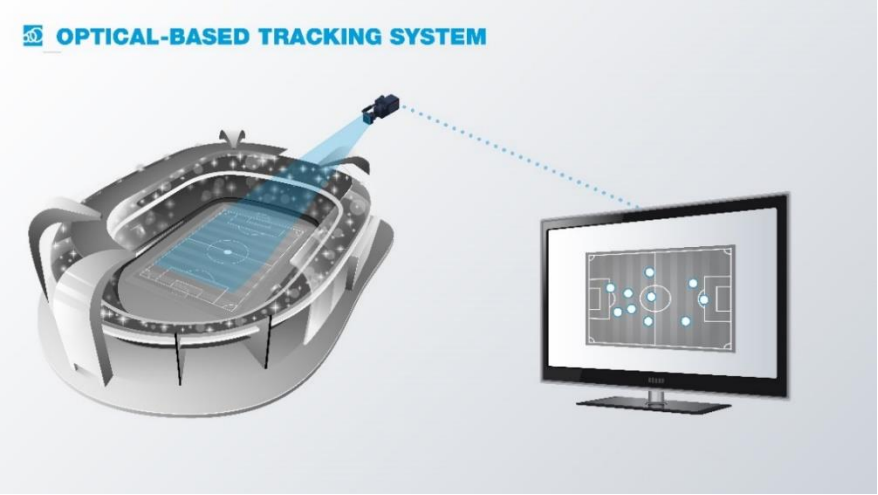
Source: Own elaboration.

The features of each one of the systems as well as their main advantages and drawbacks are mentioned below.

Optical-based tracking system

It is a system based on the installation of special cameras in the stadiums. Such cameras record the match in order to detect the movements made by the players and the ball.

Figure 4: Functioning scheme of optical tracking EPTS devices.



Source: Own elaboration.

The advantages offered by this optical tracking system are the following:

- Adaptability to any situation. Thanks to the images captured by the cameras, the position of any mark is obtained and it is stored together with the time in which the sample has been taken, so it is easier to make reconstructions with that data.
- It is a non-invasive system, since it is not necessary that the athlete wears a device on their body.
- It allows performance monitoring in enclosed spaces, such as sports halls or stadiums, with structures that would be limited with GNSS technology.
- The sampling frequency is greater than in other EPTS devices.
- It allows the monitoring of the ball.

On the other hand, the drawbacks of this technology are:

- The number of cameras that have to be installed, so that there are not dead spots and thus absent tracking locations, are avoided.
- It only provides variables of positioning that are derived from the spatial displacement, so it is not possible to analyse load parameters, such as impacts and jumps obtained through inertial sensors.
- Data cannot be obtained beyond the area of the system installation.
- The installation of the camera system takes a great deal of time and it has a high economic cost.

Global navigation satellite system (GNSS)

The global navigation satellite system is the EPTS more used in the world of sports performance analysis. GNSS is a system that, through the disposition of satellites, allows establishing the position of any player. From the positioning of the players, it can be obtained variables such as speed and acceleration.

Figure 5: Functioning scheme of the EPTS devices with GNSS technology.

Source: Own elaboration.

Their main advantages compared to other systems are:

- Its use is quick and easy, since it is only necessary to place a device on the athlete and to start the data acquisition.
- No additional installation is required, such as cameras or antennas.
- Given its simplicity, a single person is enough to be responsible for the proper functioning of the devices.
- It provides many variables for performance analysis, gathering variables of positioning and of other types of sensors, such as inertial sensors or heart rate sensors.

GNSS technology also has the following drawbacks:

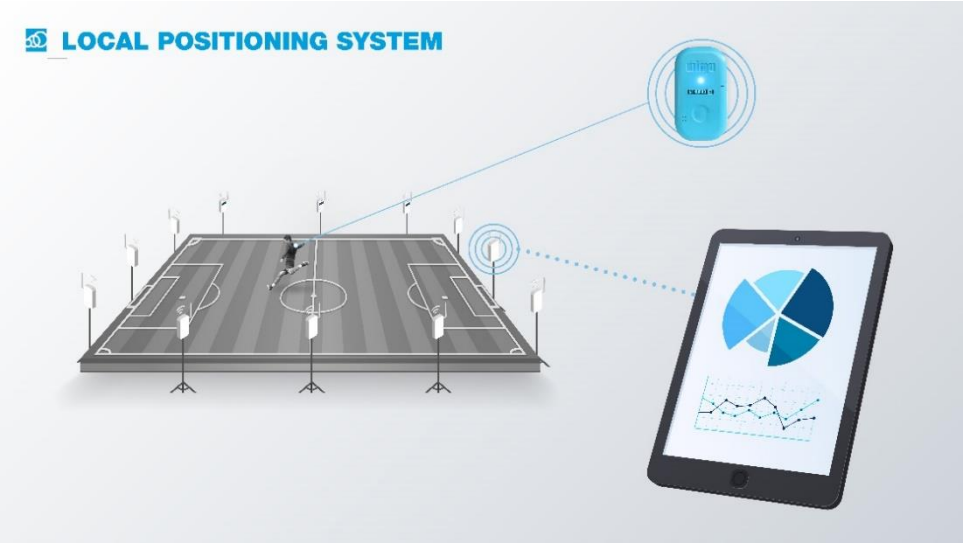
- GNSS systems do not work in closed facilities, and therefore we will only be able to track players in open spaces.
- The signal quality can be affected by weather or the retractable roofs that the stadiums may have. In such cases, by not having a strong signal, the accuracy and reliability of the data might not be the best.
- It is a technology somewhat invasive for the player, as it is necessary to place a device on them in order to obtain the data. However, this technology is becoming less invasive due to the reduction in the size and weight of the devices.
- Currently, it only allows the tracking of the athlete, not of the ball.

Local positioning system (LPS)

Local positioning system (LPS) is an alternative location system created to work in stadiums or sports venues, where sometimes GNSS technology is not fully operational. The main difference between LPS and GNSS technology is that, instead of using satellites,

LPS functions thanks to the installation of a set of antennas which allow knowing the position of the players on the field.

Figure 6: Functioning scheme of the EPTS devices with LPS technology.



Source: Own elaboration.

The main advantages offered by LPS are the following:

- It allows performance monitoring in indoor installations (sports halls) or stadiums with limited coverage for GNSS technology.
- Like GNSS technology, it provides many variables for performance analysis, since we can join variables of positioning (distances, speeds and accelerations), variables obtained from inertial sensors (jumps and impacts, for example) and variables taken from other heart rate sensors.
- It allows the monitoring of the ball.

On the contrary, it has the following disadvantages:

- It is required a fixed installation of an antenna system around the field in order to obtain high accuracy data.
- It is a technology somewhat invasive, since a device has to be placed in the player in order to obtain the data.
- The economic cost of the LPS installation is relatively high.

Components of GNSS and LPS devices

Given its economic costs and the simplicity of it use, GNSS devices are actually the more frequently used in the sports performance field. Besides these devices with GNSS technology, there are EPTS in the market that allow working with GNSS and LPS technologies integrated in a same device, which allows taking data from both technologies indistinctly (as long as they have LPS antennas installed).

Figure 7: Necessary elements for the use of EPTS devices: electronic device and vest.

Source: Own elaboration.

For the use of GNSS devices, the following elements are required:

- **Electronic EPTS device:** it allows, among other options, the reception of signals from GNSS satellites, data registration and data storage. At the same time, this electronic device is composed by:
  - **Microprocessor:** it is a central integrated circuit which enables the device to carry out all the logic and arithmetic operations, from the operating system of the device to the application software.
  - **Internal memory**: the device comes with an internal memory that allows the storage of all the information collected during the data acquisition.
  - **GNSS/LPS receiver:** it is the component that allows the signal reception of GNSS satellites or local positioning systems satellites (in the case that the device has this option).
  - **Inertial systems:** an inertial system, also called inertial measurement unit (IMU), it is an electronic system generally composed of accelerometers, gyroscopes and magnetometers (one by each movement axis), in order to obtain measures of speed, rotation and gravitational forces. Normally, a pressure sensor (barometer) is added, although it is not considered an inertial sensor.
  - **Connection systems**: another characteristic of some EPTS is its ability to connect to other type of sensors, such as heart rate monitors, measurement devices of oxygen or electromyography. The connection technologies that work today are: WIFI, ANT+, Bluetooth and Zigbee. Furthermore, they also have a micro USB that allows the device to be connected to the PC for information downloading or the battery charge.
  - **Battery:** it allows the device to work without the need of being connected to a power outlet. It is essential to know the exact duration of the device battery to prevent it from turning off during training or competition sessions. Normally, these batteries last between 4 and 5 hours.

- **Vest or training bib:** It allows the placing of the device in the player's back, right between their shoulder blades. It is essential to place it correctly, because otherwise it is possible that the measurements that will be taken will not be completely accurate. According to the objective pursued (for example, range of motion valuations, impact studies, etc.), the device can be placed in other parts of the player's body.

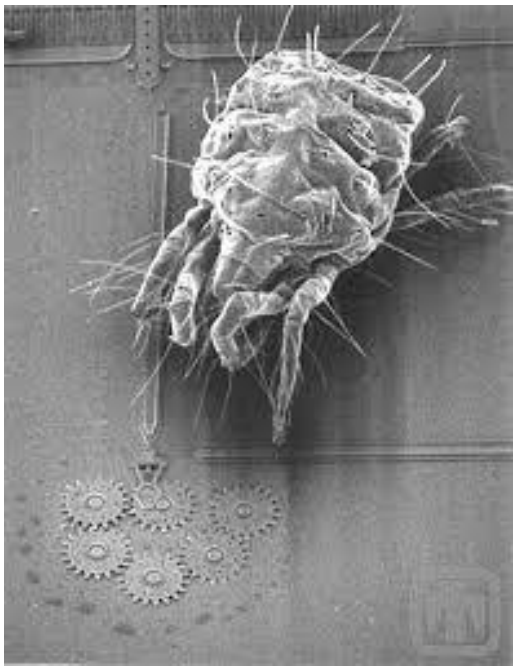
Inertial systems of EPTS devices development

EPTS devices have inertial sensors that measure the movement, acceleration or angular velocity of the players through the use of accelerometer and gyroscopes. In this way, they offer performance variables such as jumps and impacts, among others.

The practical implementation of this type of inertial sensors emerged in the 20s, mainly in air and space navigation. In those years, the main problem presented by these devices was that its size, weight and consumption were relatively large. For these reasons, it was difficult to use them in other type of situations where smaller and lighter devices would have been necessary.

In the 80s, it was presented the first inertial sensor developed by microelectromechanical technology (also called MEMS). This technology, besides having a lower cost in comparison with others of sensor manufacturing, allows the creation of tiny devices, in which the components that make it up have sizes ranging from one to 100 micrometres (UNAM, 2003). In figure 8, we can see an example of the size of these MEMS sensors in comparison with a dust mite.

Figure 8: Dust mite near a MEMS sensor. Sandia National Laboratories.



Source: [Untitled image of a dust mite near a MEMS sensor. Sandia National Laboratories]. (2019). Retrieved from https://es.wikipedia.org/wiki/Sistemas_microelectromec%C3%A1nicos

In this way, with MEMS, we are capable of creating smaller, faster, cheaper and more efficient systems, as accelerometers and gyroscopes with characteristics of size, cost, measuring range and sensitivity fully suitable to be implemented in fields such as medicine or high performance sport, in which lightweight equipments are needed in order to avoid altering natural movements. In short, their large number of applications make MEMS sensors a fundamental part in the technology (UNAM, 2003).

In the subsequent unit we will see exactly how MEMS sensors work, and focus specifically in the functioning of the accelerometer, the gyroscope and the magnetometer. Moreover, we will analyse the information and the performance variables they offer.

EPTS use regulation and its evolution: IMSS certification

FIFA's Football Technology Innovation Department has worked for years on the standardization of electronic performance & tracking systems (EPTS) in football and, finally succeeded in establishing use regulations of EPTS in official competitions. In order to talk about the use regulation of EPTS devices, we should mention the International Football Association Board (IFAB) that is the body in charge of defining the laws of football worldwide. Since its origins, at the end of the 19th century, the IFAB has assumed a fundamental role and has worked as regulatory body of the **Laws of the Game.** It is responsible for ensuring the compliance with the laws, as well as studying and modifying them if necessary.

If we make a brief view over the evolution of the tracking systems applied to team sports such as football, it was in the year 2015 when FIFA established the laws and controlled the use of these devices under the acronym EPTS. The first official test was made during the 2017 Confederations Cup and the systems became official in 2018 World Cup Russia.

The process of the EPTS devices use regulation is shown below:

Figure 9: Evolution of the EPTS devices use regulation

Source: Own elaboration.

Year 2015:

- It all started on 28 February, in the 129th Annual General Meeting (AGM) of the IFAB in Belfast, it was informed that a great number of clubs were using EPTS devices in the training sessions in order to monitor the load and to improve the player performance. It was also informed that the IFAB had also received the request for the use of these devices in official matches.
- Later, in **May** of that same year, the IFAB published the Law 1 (IFAB, 2015) in which the changes in the **Laws of the Game 2015-2016** are accepted. In this Law, the IFAB notifies that the use of tracking systems is approved, but that more investigations will be needed to evaluate the quality and accuracy of these systems, the data usage and the licensing process. It also makes it clear that, although it has been granted the permission to use the devices in official competition, their use will always depend on the authorisation of the member association or of the organiser of the competition in question.

  Therefore, it was agreed upon Law 4 **"The players' equipment"** (IFAB, 2015, p. 2) which:
  - If **electronic performance & tracking systems** are used, the following conditions must be met:
    - "EPTS devices must not pose any danger to the players and match officials.
    - Information and data transmitted from the systems are not permitted in the bench or the technical area during the match" (IFAB, 2015, p. 2).
- In **October**, FIFA, along with the IFAB, invited (in Zürich, Switzerland) the manufacturers industry of EPTS devices so that they introduced their systems to

both organizations. There, they were able to know more about the functioning of those systems.
Given the interest of the clubs in using EPTS systems in competition, the IFAB asked FIFA to develop a quality programme, similar to "FIFA Quality Programme", which was introduced in 1996 for the turf, the ball, the goal line, etc.

Year 2017:

- The **Laws of the Game 2017-2019** (IFAB, 2017) came into force in **June**. In which, the IFAB incorporated the regulation that controls the application of EPTS systems in official matches. At that year's version, the following regulation was added:
  - The players are not allowed to use any electronic device unless it is an **electronic performance & tracking system.** Nor will the technical staff be able to use electronic systems for communication except for safety or welfare of the athlete (IFAB, 2017).
  - When players use EPTS devices in a competition under the auspices of FIFA, confederations or national football associations, the competition organiser must ensure that the devices attached to the player's equipment are not dangerous and that they bear the **International Match Standard (IMS)** mark (IFAB, 2017)**.**

Figure 10: Certification Seal of International Match Standard (IMS)

This mark indicates that the EPTS device has been officially tested and meets the requirements in terms of reliability and accuracy of positional data in football. It also indicates that it meets the minimum safety requirements of the International Match Standard developed by FIFA and approved by IFAB. The institutes conducting these safety and reliability tests are subjected to the approval of FIFA.
This certification is a mandatory requirement from 1 June 2017. For the systems that are already in use, the transition period to get it runs until 31 May 2018 (IFAB, 2017).

- **2 July 2017**, the first official test was run in the Confederations Cup Final, in Russia. There, Chilean and German teams wore electronic performance & tracking systems.
- In **October,**the quality programme of FIFA was published: **FIFA Quality Programme for wearable EPTS devices.** This document informed the manufacturers and the industry of EPTS devices about how to obtain the International Match Standard.

Year 2018:

- In May, it was presented the definitive regulations for the use of EPTS devices in the 2018 World Cup Russia. Additionally, FIFA informed that, during the World Cup, it will be offered the technology that allows the analyst not only to connect from its bench, but also to analyse the physical performance of each player by means of electronic devices that aim to improve the performance. Furthermore, a camera system will collect data of the positioning and spatial displacement of the players and the ball, transferring this data to the analyst in real time.
- **31 May** was the end date of the transition period for the manufacturers of EPTS devices to obtain the IMS certification of FIFA so that their devices can be used in official competition.
- The "Laws of the Game 2018-2019" (IFAB, 2018) came into force in **June**. In this version, it is added that the use of any form of electronic communication is permitted where it relates to tactical reasons but only small devices (microphone, headphone, mobilephone, smartwatch, and tablet). A member of the technical staff who uses unauthorised equipment or misuses those admitted will be dismissed from the technical area.
- A reference standard, which is added to the previous regulation, was developed by FIFA and approved by the IFAB in order to support the leagues and competition organisers with the approval process of reliable and accurate EPTS. This standard will be implemented in the transition period that will run until 1 June 2019.

Year 2019:

- The transition period ends **1 June**, and from that date on, the application of the professional standard by the FIFA is a reality. The logo shown on figure 11 indicates that the EPTS device has been officially tested and meets the requirements in terms of reliability and accuracy of positional data in football.

Figure 11: Certification Seal of FIFA Quality

Source: Reglas de Juego 2018/19, IFAB, 2018, p. 45.

1.2 Aspects related to EPTS

In unit 1, it has been seen what EPTS are about, how many types there are and the evolution it has had over the years. Now we will explain in depth the characteristics of some EPTS, specifically GNSS devices.

On one hand, we know that GNSS are, currently, the most used in the sports performance world. For this reason, it will be shown in detail what these systems are based on, their main characteristics and the possible sources of errors that their measurements may bring.

On the other hand, EPTS are not only player tracking systems but they are also made up of microelectromechanical components which allow monitoring athlete performance. For this reason, we will also explain what these components are based on, what they measure, and how they can be helpful in the sports performance field.

GNSS: Global Navigation Satellite System

First of all, before explaining how GNSS devices work, it is important to clarify some concepts that may cause confusion. Global Navigation Satellite System or GNSS is a constellation of satellites that orbit the Earth and calculate the position of a receiving antenna. At present, the use of these devices is wide-ranging and we can find them in fields of navigation, transport, agriculture and, among others, sport.

There are different GNSS devices depending on the constellation that is being used. Figure 12 shows the most well-known GNSS constellation classification.

Figure 12: Classification of GNSS constellations

Source: Own elaboration.

The most known GNSS is the Global Positioning System (GPS) that is the system created by the U.S. Department of Defense in the 70s. We also find other models, as GLONASS, created by Russia; GALILEO, controlled by the European Union (it is not yet operating) and BeiDou, controlled by China.

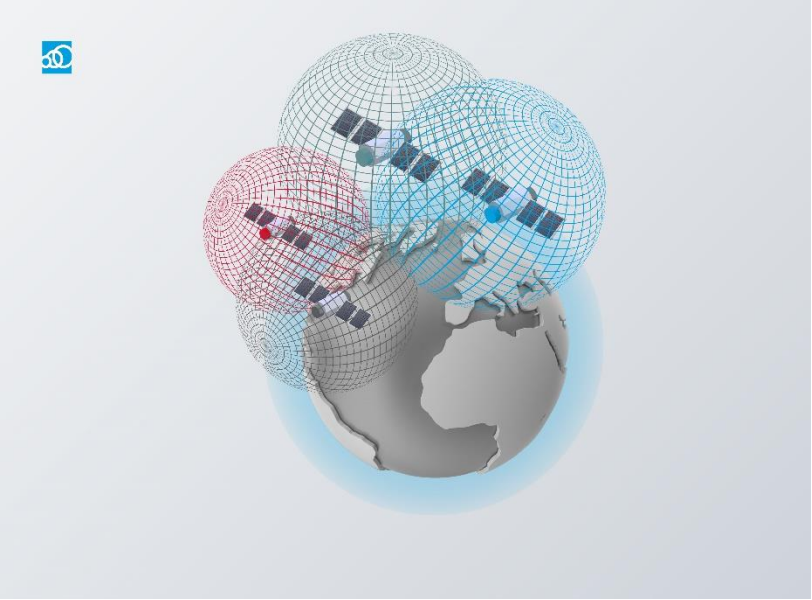
GPS is used to make reference to the receivers which work solely and exclusively with GPS signal, while those that integrate various systems at a time are called GNSS receivers. Nowadays, the tendency is to work with multifrequency receivers capable of processing the signals of different systems.

Functioning of GNSS

The global navigation satellite systems are somewhat complex. There are mathematical and physical foundations that explain their performance and their subsequent implementation. Basically, a GNSS is a system with a constellation of satellites (from 24 to 27) that move in different orbital planes around the Earth.

In order to get the positioning of a receiver (in our case, a player), the detection of at least 4 satellites is required, and through the technique of 3D trilateration (Berrocoso, 2009), longitude (x), latitude (y), altitude (z) and time (t) are determined, as shown in figure 13. In the case of using only 3 satellites, the positioning will be determined in 2D, without finding the receptor's altitude.

Figure 13: Technique of 3D trilateration to know the receiver's position



Source: own elaboration.

In relation to figure 13, the point which integrates each one of the spheres indicates the position with regard to the GPS receiver.

In the sports performance world, the most interesting variables provided by GNSS devices are the position and its derivatives: distance, speed and acceleration.

GNSS sampling frequency

In the last few years, the sampling frequency of GNSS devices has been an important and extensively discussed issue in scientific literature. A low sampling frequency means that we will obtain few data per second. For example, if the sampling frequency is not high enough, the acceleration values will not be fully accurate with this type of devices.

The first GNSS devices operated at 1 Hz and obtained only one datum per second of sampling. As technology evolved, 5 Hz devices appeared, which implied a great advance with regards to the previous devices (Muñoz, Granero, Pino & De Hoyo, 2017). At present, in the sports performance world, GNSS devices operate at more than 10 Hz. Although this frequency is still lower than the sampling of inertial sensors, we can say that any human movement is easy to register and, besides, the accuracy of the data can be relied.

This way, and with advances in technology, it is probable that, in the near future, these devices are used more frequently, which will help obtain a greater amount of data.

Potential sources of error

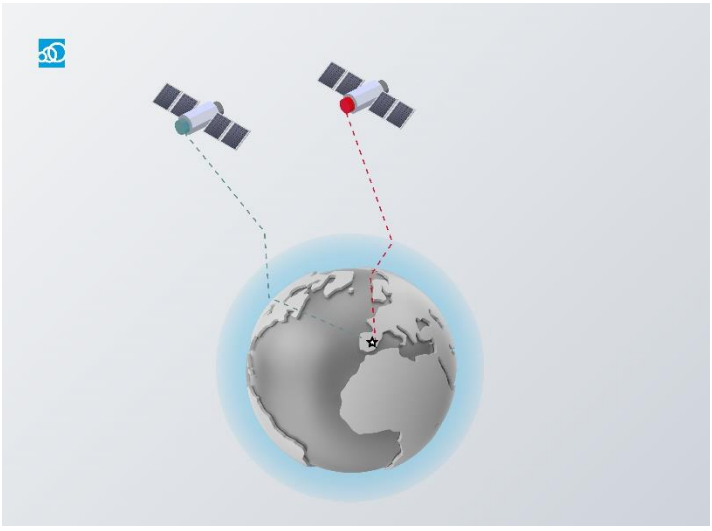
As stated earlier, the quality with respect to the signal of the GNSS devices is delicate, either because of climatic reasons or because of the retractable roofs that can be observed in the stadiums. In these cases, by not having a good signal, its accuracy and reliability may not be the most correct.

Belowshows the main sources of error that we can find when receiving a GNSS signal.

Ionospheric delay

One of the major sources of error is weather conditions, because the atmosphere (ionosphere and troposphere) refract the signals of the satellites. When the satellites go through the atmosphere in their way to the earth's surface, it causes a change in the propagation speed of the GNSS signal. As shown in figure 14, the signal of the satellites divert during its passage through the ionosphere and the troposphere and this leads to measuring errors on Earth (Prieto & Velasco, 2013).

Figure 14: GNSS satellite signal refraction during its passage through the ionosphere and troposphere.



Source: Own elaboration.

On one hand, the stratosphere is the layer in which a highest rate of error is generated, because a high level of electrons is present, such as positives ions, produced by solar radiation, which has a negative impact on the signals. There are several factors that influence the delay caused by the ionosphere, such as its density or the elevation in which the satellite is found. On the other hand, in the troposphere, there is a large amount of water vapour, giving rise to other type of satellite signal refraction.

Time of the satellites

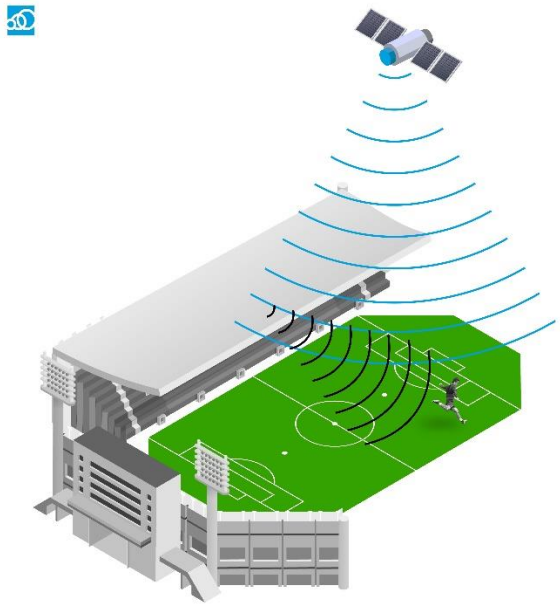
The clocks of GNNS satellites are atomic clocks of high precision, but they may cause a drift over time because of noises or gaps produced by the action of the relativistic effects. These errors may lead to the existence of a difference between the timing system of the satellite and the receiving system. This error is not constant for all the satellites, as it varies from one to another (Prieto & Velasco, 2013).

Multipath

The multipath error occurs when the receiver is located near a large reflective surface, such as buildings or mountains, and the satellite signal arrives first to the nearby object and then is reflected to the receiver, causing a measurement that is not completely accurate (Prieto & Velasco, 2013, p. 43).

This type of error is extremely common in movement receivers and it may cause a positioning error of several meters. This phenomenon takes place in stadiums with retractable roofs, as shown in figure 15, where the GNSS signal bounces off the stadium roof and influences the accuracy of the signal that is received from the player, which is somewhat unclear.

Figure 15: Visualisation of multipath effect in a football stadium



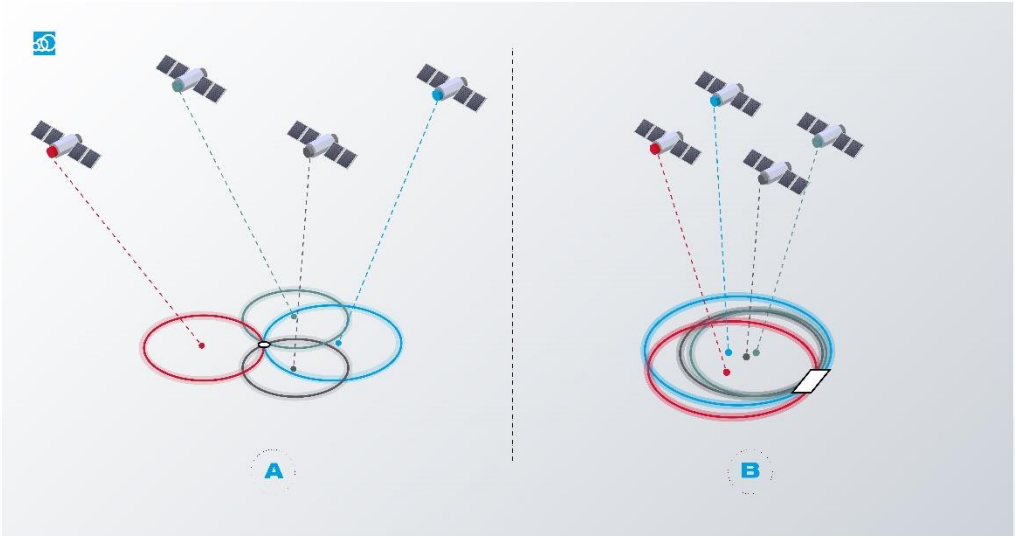
Source: Own elaboration

Satellite geometry and dilution of precision (DOP)

It is known that the number and position of the satellites is as important as the geometry that their signals describe and deliver. **Dilution of precision** (DOP) is a value that provides information about the strength of the geometric arrangement, made of the receiver device and the vectors that determine the receivers with the satellites (Langley, 1999).

In figure 16 (part a), it can be seen that if the satellites have a better spatial distribution, the calculation of the position- through triangulation- is much more accurate than f the satellites had a worse spatial distribution.

Figure 16: Different spatial distributions of the satellites



Source: Own elaboration.

The following parameters provide an approximation to the precise disposal of the satellites to know, in this way, if the data collected is accurate and reliable.

- **Geometric DOP (GDOP):** it provides information about the uncertainty of the user's position from the geometric arrangement of the satellites and of the temporal precision.
- **Position DOP (PDOP):** it provides information about the uncertainty of the user's position only taking into account the geometric arrangement of the satellites.
- **Vertical DOP (VDOP):** it provides information about the uncertainty of the user's vertical position.
- Horizontal DOP (HDOP): it provides information about the uncertainty of the user's horizontal position.

Inertial sensors: IMU (inertial measurement unit)

An inertial measurement unit, also called IMU, is an electronic device generally composed of accelerometers, gyroscopes y magnetometers (one by each movement axes). Its objective is to obtain measures of speed, rotation and gravitational forces.

The accelerometers are placed in a way that their measuring axes are perpendicular. They measure the inertial acceleration, also known as g-force. Furthermore, gyroscopes are placed in a similar orthogonal pattern and they measure the rotational position. Lastly, magnetometers are also in an orthogonal shape and they allow knowing the orientation of the device.

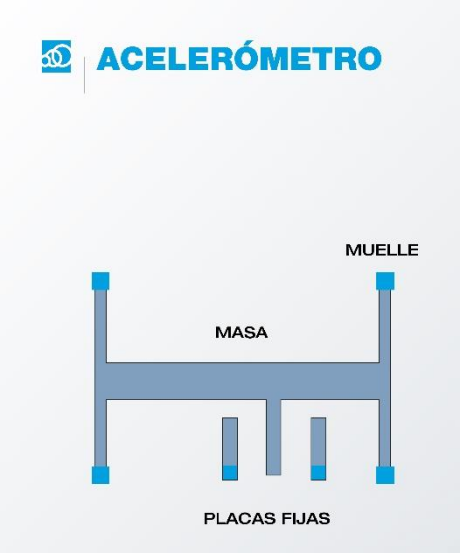
Below is brief explanation of these sensors' composition, as well as some of their main characteristics.

Accelerometer

An accelerometer is an electromechanical device capable of measuring acceleration forces. Such forces may be static (like the gravity force), or dynamic, caused by the movement or the vibration of the accelerometer.

The accelerometers that make up the inertial systems are generated from microelectromechanical technology or MEMS. They are composed of capacitors, made of movable and fixed plates attached to a mass (figure 17), and they provide the signal when they spot changes in the capacitance or electrical capacity (Andrejašič, & Poberaj, 2008; Yazdi, Ayazi, & Najafi, 1998).

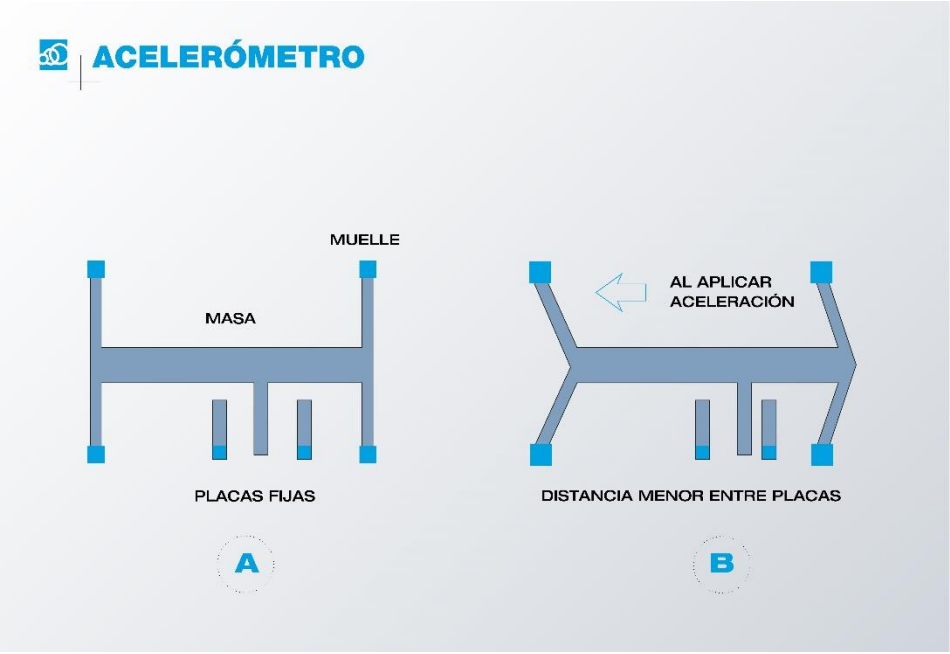
Figure 17: Layout of a MEMS capacitive accelerometer



Source: Own elaboration.

The system is at rest in the absence of acceleration, that is to say, when the device is static or it moves at a constant speed (figure 18, part A). Once the device suffers acceleration, a force acting in opposite direction to the movement appears and causes all the system to move. The mass opposes a resistance to the change in position and presents a relative movement between itself and the fixed plates (figure 18, part B). This movement changes the capacitance value, so that an output voltage is obtained that is proportional to the magnitude of the force at which the accelerometer is being subjected (Capistrán & Paredes, 2005, p. 22).

Figure 18: Layout of the MEMS accelerometer functioning



Source: Own elaboration.

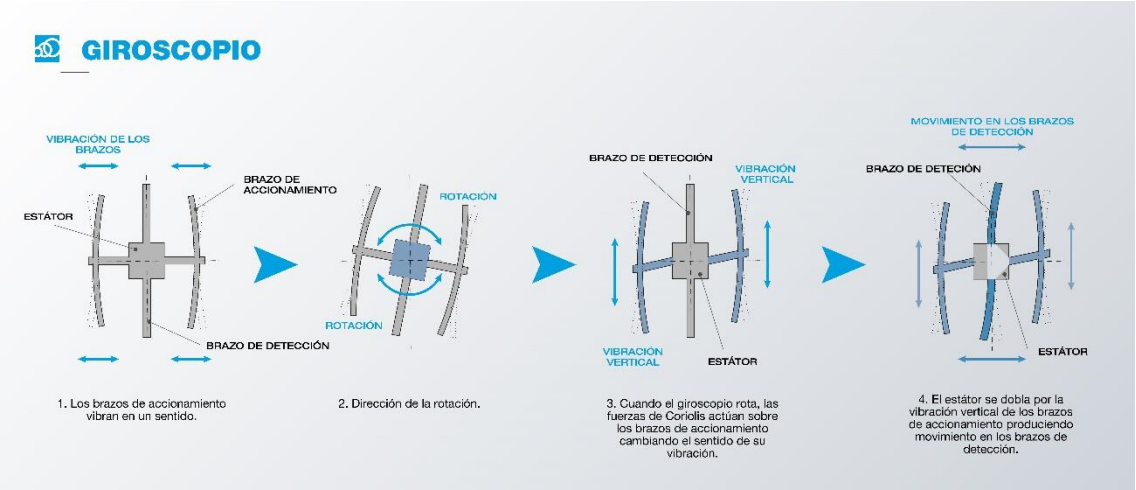
The use of these devices in sports will allow the registration of the total amount of movement that the players perform in the 3 movement axes (x, y, z) and it will facilitate the measuring of (among other variables) impact forces to which they are subjected, number and intensity of the steps, etc.

Gyroscope

A gyroscope is an electromechanical device that measures the angular velocity of a body based on its functioning in the **Coriolis Effect** (Esfandyari, De Nuccio, & Xu, 2010). This phenomenon is executed in a rotation system when a body is in motion with respect to the system. This indicates the presence of the body's relative acceleration in the rotation system, which is characterized by being perpendicular to the rotation axis of the system and to the speed of the body.

As the accelerometer, the gyroscope is generated through the MEMS technique, and, specifically, the one used in EPTS devices has a **tuning fork** configuration. This configuration is composed of two masses that oscillate and move constantly in opposite directions. When angular velocity ω is applied to the device, the Coriolis forces resulting from each mass also act in opposite directions, which results in capacitance change, so that an output voltage is obtained which is proportional to the magnitude of the angular velocity ω at which the gyroscope is subjected (Esfandyari et al., 2010).

Figure 19: Layout of the MEMS gyroscope functioning



Source: Own elaboration.

In short, EPTS gyroscopes allow the monitoring of the players' rotational speed, among others. Moreover, it is a useful tool at a biomechanical level, since it allows studying the execution of a movement in detail.

Magnetometer

The magnetometer are measuring sensors of magnetic field and, specifically, of earth's magnetic field. In simple words, the magnetometer may resemble a compass. Just like accelerometers and gyroscopes, it is also a MEMS sensor.

The operating principle of magnetometers relies on the measurement through magneto-resistance which changes its value according to the field that breaks through it using AMR sensors (*Anisotropic Magneto Resistive*) (Quynh, Tu, Thy, Viet, Duc, Phung, & Giang, D. T 2019). These changes in resistance trigger voltage variations that allow the device to find the vector towards Earth's magnetic north.

It must be taken into account that the magnetic fields caused by the proximity to an electric current or by a magnet also influence the magnetometer measurements. Thus, it is important to avoid possible interferences, such as the use of a magnetometer near a metallic object, as they may cause wrong measurements.

The magnetometer can help in the high-performance sport world, since the data it offers can may merge with that of the accelerometer and of the gyroscope for determining the movement, the orientation and the direction of the player.

Barometer

The barometers are sensors that allow measuring pressure differences and they can be useful when a movement in the vertical plane occurs. These types of sensors are not considered inertial sensors as the accelerometer and the gyroscope; however, they are implemented in inertial measurement units (IMU). In this case, the barometer is a MEMS sensor.

The operating principle of the barometer is simple: a pressure variation causes the piezo-resistive material of the sensor to modify its resistance. These changes in resistance cause voltage variations that allow the calculation of the exact pressure differences.

Sensor redundancy and fusion

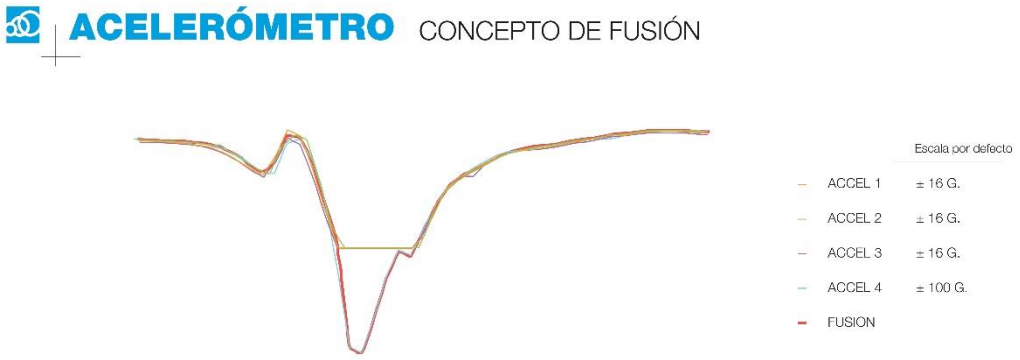
In many cases in which inertial sensors are used, such as in the industry and in the air navigation, the concept **sensor redundancy** is used. This is based on the placement of more than one sensor in order to perform the same function and obtain more robust and precise data.

At present, there are certain EPTS that use sensor redundancy. In figure 20, there is an accelerometry signal of one of these devices and it is composed of 4 accelerometers. The maximum measuring range of each of them is illustrated in the right side of the figure.

As shown in figure 20, there are 3 accelerometers adjusted in such a way that they measure up to the 16 G threshold, while there is a forth accelerometer that can measure up to 100 G. The system merges the signals of these 4 accelerometers and, consequently,

the result obtained is much more robust than if the result came from the signal of a single accelerometer.

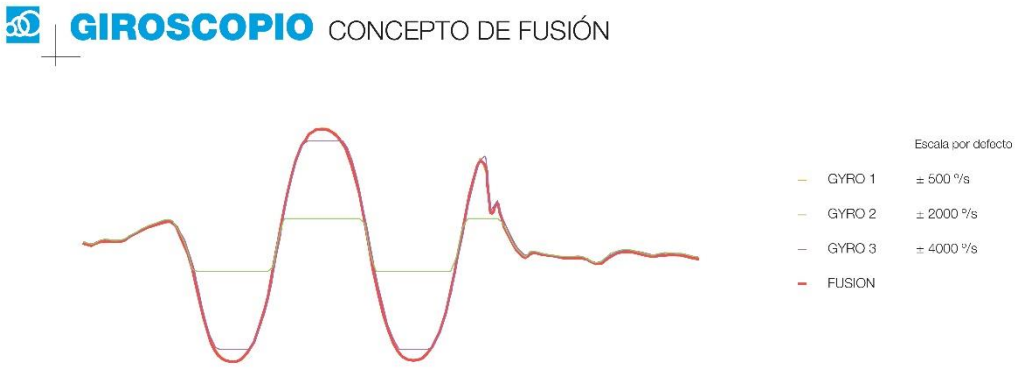
Figure 20: Accelerometry signal with sensor redundancy



Source: Own elaboration.

In the case of the gyroscope signals, the same process as in the accelerometers is used, but the fusion comes from 3 gyroscopes configured at different scales (figure 21)

Figure 21: Gyroscopes signal with sensor redundancy



Source: Own elaboration.

Sensor calibration

The decrease in size and in cost of inertial sensors enables the sensors to have a myriad of application in many fields (engineering, sports, and navigation); nevertheless, they imply losing the accuracy of the data obtained. For this reason, and in order to correct the accuracy mistakes that may happen, it is necessary to carry out a calibration before starting the data acquisition. Normally, the inertial sensors of EPTS devices already have a self-calibration procedure and, through programming algorithms, the mistake or drift that may exist is corrected.

It is necessary to take into account the possible interferences that may appear when it comes to calibrating these devices. For example, the magnetic fields caused by the proximity to an electric current, a magnet or a near metallic object, may cause the sensor calibration to not be correct and the reliability of the data taken subsequently to not be the one desired. In order to correct the possible interferences, it is recommended that, during the calibration procedure, the device is static and, furthermore, in a place free of external influences (magnetic fields, ferromagnetic materials, etc.). Finally, it is suggested that the self-calibration procedure of the device is made in the same place where it is going to be used.

Sampling frequency of inertial sensors

Like the signal of GNSS satellites, the sampling frequency of the inertial sensors is also important when it comes to the interpretation of the data obtained. Nowadays, the majority of EPTS devices available in the market work with a frequency of 100 Hz, which means obtaining 10 pieces of data for each datum of the GNSS signal (10 Hz). There is also the option to modify the frequency and to configure it to 10, 100 or 1000 Hz.

Virtual attitude sensor

The attitude sensor is calculated thanks to the combination of inertial sensors: accelerometer, gyroscope and magnetometer. The attitude sensor allows knowing the orientation of an object with respect to an inertial reference or any object of interest. It is important to emphasize that this sensor only calculates the object orientation and not its position.

We know that the movement made by a rigid body with a fixed point is determined by knowing the Euler angles. Then, a brief explanation will be made of what this Euler angles are and what kind of information they provide.

Euler angles

Euler angles or rotations are a set of 3 angular coordinates that serve to distinguish the orientation of a mobile reference system of perpendicular axes (x, y, z) with respect to other fixed reference systems with orthogonal axes (Quynh et al., 2019).

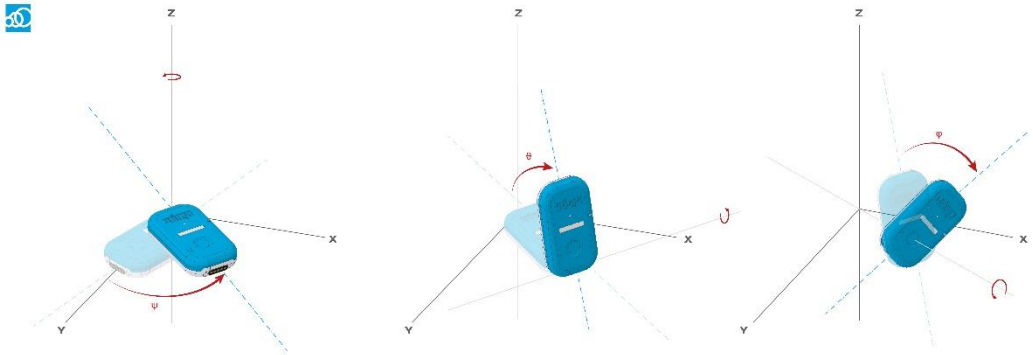
In this way, we can define the attitude of a player by distinguishing three rotations of different nature:

- **Precession (φ):** it is the rotation of the body around a fixed system. That is to say, the angle that measures the laps made by a player on the football field.
- **Nutation (θ)**: it represents the inclination of the player with respect to the vertical. In this case, it refers to oscillation angle of the vertical axis that has been selected as guide for the mobile body with respect to the vertical axis of the fixed system.

- **Spin (ψ)**: it is produced when the player spins around, in other words, it is associated with the angle that measures the spins made by the mobile body in its own axis.

Figure 22 shows the three rotations/angles in the player, as cited above.

Figure 22: Display of the different Euler angles or rotations



Source: Own elaboration.

On a practical level, Euler angles allow knowing the orientation of each one of our players in the field. In biomechanical analysis, this will be very useful since it allows calculating ranges of joint motion, among many other variables.

In the next modules, we will address practical applications of these sensors, how they can be implemented in the study of the performance and what variables can be obtained.

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