Development of innovative training solutions in the field of functional evaluation aimed at updating of the curricula of health sciences schools

MODULE BIOMECHANICS FOUNDATIONS

Didactic Unit D: TECHNIQUES FOR THE INSTRUMENTAL ANALYSIS OF MOVEMENT AND FORCES

D.1. How can movements be measured and which parameters can be analyzed? What are its main applications?

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1. Introduction and objectives

Remember that kinematics or movement analysis combines knowledge from different methodologies in order to obtain qualitative and quantitative variables and describe movement regardless of the forces that generate it.

The equipment used in the study of the biomechanics of human movement has undergone great advances in recent times, from manual annotations on photographs to marker-based optical tracking systems, systems based on inertial sensors, and marker-less analysis systems that use sophisticated models, computer vision, and complex machine learning algorithms [1].

Motion analysis systems have evolved in parallel to the demands of areas such as animation for video games or cinema, developing faster and more powerful tools to bring clinical and sports biomechanical assessment beyond laboratory research.

The **objectives** of this didactic unit focus on:

- The major groups of movement analysis techniques.
- Understanding how they work, and the information they provide.
- Their main advantages and disadvantages.
- Introducing the areas where kinematic instrumental techniques for motion analysis are used.
- Some examples of use and systems based on these instrumental techniques.

To facilitate the study, a general classification based on the type of sensor or device used is included (Figure 1).

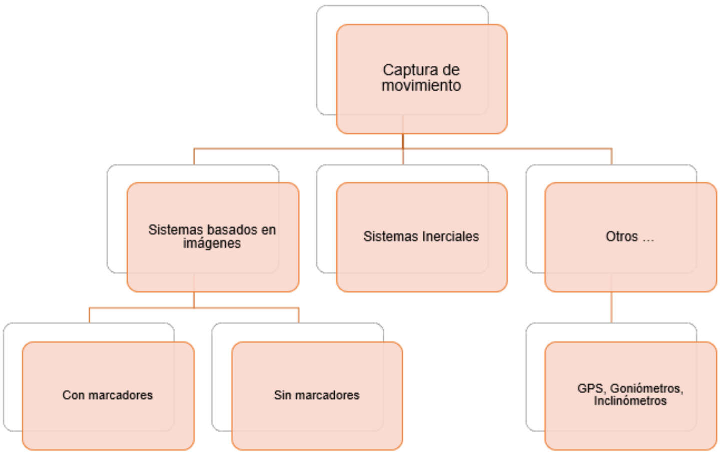

Figure 1 – Classification of motion analysis systems.

2. Movement analysis systems based on images

Since the introduction of movement analysis in biomechanical assessment, the most widespread methods are based on optical systems, which study the object to be measured using tools that record images.

Image-based motion analysis systems are currently considered the gold standard in the biomechanical study of movements, including human functions and activities. These optical systems, based on different types of cameras, extract the necessary information from sequential images or videos in order to describe the movement that occurs. Such information is extracted by using different signal processing methods, depending on the equipment.

Optical technology for motion analysis uses cameras and lighting specially configured for the system used to observe the object being assessed in a simple way. The data to track its displacement over time can be obtained by identifying points or markers that represent the object through consecutive images.

The estimation of the position (3D) and orientation (3D) are the main variables required by an optical system to establish the 6 degrees of freedom (DoF) or the pose of an object. These variables, together with other variables extracted from the kinematic study such as speed and acceleration, allow us to study the movement of the body or its segments independently, or in interaction with objects and/or environments over time.

The frequency of acquisition and the image resolution of the systems are fundamental characteristics to extract the kinematic variables that study the displacement of the segments; they also influence the selection of the movements to be studied and the precision of the results.

Due to the complexity of the human body because of its multiple joints, the partial stiffness of its segments, etc., the biomechanical study draws on kinematic models, which are more or less complex simplifications to analyse movement. The study models are created by placing markers at specific anatomical points according to an established protocol that depends on the anatomical area or segment or on the movement to be analysed [2].

In 1973, the International Society of Biomechanics (ISB) was established with the aim of promoting the study of biomechanics https://isbweb.org/. Since 1990, the ISB has worked to provide recommendations for standardisation in the reporting of motion analysis data. These proposals for standards are related to the definition of global, articular and orientation coordinate systems, as well as models of different joints and body segments.

When the information about a movement occurs in a plane (2D), simpler models are normally used with only one camera (monocular view). When the movements are more complex and occur in various planes (3D), a more complex model and a multi-camera (multi-view) system are required, where the marker is placed and followed by multiple cameras. It is recommended that at least three cameras locate a marker to perform a robust 3D reconstruction from the information obtained by each camera.

The 3D reconstruction of a movement by equipment that uses multiple views is more accurate than if only one camera is used to reconstruct this information based on data from a single plane.

Another difference between performing a 2D or a 3D analysis is the generation of more complex processes of calibration and reconstruction of coordinates, as well as the definition of the joint angles [1].

The processes that make up these systems can be established as follows (Figure 2):

- Calibration. A reference system whose geometry and dimensions are known is used to calculate the adjustment parameters.
- Detection (digitization). Identification of the points that define the selected model.
- Tracking. The tracking is performed by the cameras during the movement to be analysed. During the entire recording, the defined points or markers must not be hidden from the cameras to avoid problems in the next phase.
- Reconstruction. The references used to create the biomechanical model are identified in the recorded images and their positions are obtained in a 3D coordinate system.
- Analysis. Treatment of the information previously obtained to extract the defined variables.

Figure 2 – Diagram of the processes involved in the use of optical systems.

The systems that process information from multiple cameras typically require a controlled environment, increased processing power, and expensive infrastructure like motion analysis laboratories, whereas 2D analysis systems are more versatile and less expensive. The selection of the equipment depends on the variables and the necessary pressure for the movement to be studied.

This didactic unit classifies the optical equipment in two large groups based on whether they use or not **physical markers** to identify references, points or objects that make it possible to establish a model to reconstruct the movement in 2D or 3D.

Marker-based systems

Optical equipment of 3D stereophotogrammetry

This equipment usually consists of a set of **cameras** that cover the space where the movement occurs from different perspectives, and the **analysis software**.

The placement of the cameras is essential to identify the markers located on the subject or on the object. The angle and distance between the cameras, their position in relation to one another (parallax), in relation to the object studied, etc., as well as the frequency of acquisition and the resolution of the cameras, they are all essential conditions to efficiently identify the markers, preventing them, for example, from getting hidden and lost in the recordings performed. In this way, the optimal conditions are established to extract the spatial coordinates of the markers, define the model for the study and extract the determined variables.

To do this, each camera collects information about the position of the marker or markers that are within its field of vision and establishes their position in a local reference system of the camera itself. This would be enough to perform a two-dimensional analysis. However, if you want to obtain three-dimensional information, the information extracted from each camera is integrated through stereophotogrammetry techniques that allow us to reconstruct the marker's coordinates in 3D, establishing its position and orientation in a global reference system. Based on this information, variables such as the angles between segments defined in the model of markers can be obtained (Figure 3).

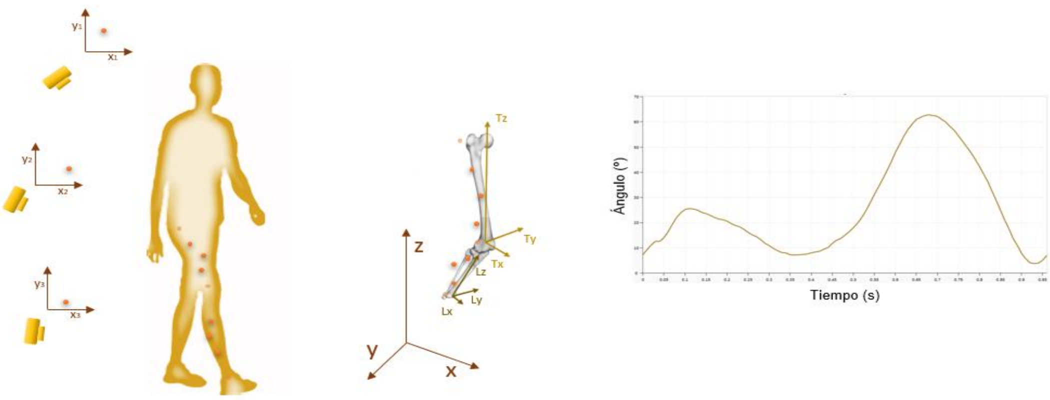

Figure 3 – Acquisition of the knee angle during gait using an optical system of 3D stereophotogrammetry.

The markers used in these systems can be **active**, based, for example, on LED light, or **passive**, like spheres coated with reflective material [3] that return the reflected light back to the camera sensor. The advantage of active markers over passive markers is that they can provide more robust measurements, but their disadvantage is that they need batteries and cables, which can interfere with the subject's freedom to perform specific movements. In addition, the sampling rate of the cameras decreases when a set of multiple markers is used because the signal from each marker needs its own frequency to be individually identified [4].

In the case of reflective markers, each camera has a focus of infrared (IR) light that they emit over their field of vision. In this way, the light emitted bounces off the markers and is captured by the camera's sensor. These sensors have filters that reject natural light and collect only the IR radiation scattered by the markers. In this case, the camera sensor detects a white point in each marker detected, the diameter of which depends on the size of the marker, the distance from the person to the marker, the resolution of the sensor, etc. The system uses the centroid (centre point) of this white point to determine the necessary calculations and the position of the marker in relation to the sensor. The models used can constitute one or several segments or the whole body depending on the purpose of the analysis.

These systems can reach frequencies ranging from 100 Hz or frames per second (fps) to 500 fps; however, the higher the frequency, the lower the resolution is, which may affect the correct identification of the markers and the calculation of variables. The selection of the frequency of acquisition depends, for example, on the speed of the movement assessed. The faster the movement is, the more events occur in shorter periods of time; for that reason, if you want to collect all the information, you need to increase the frequency of capture. As an example, to analyse a golf swing movement, a frequency of 250 Hz is needed, whereas human gait at normal speed can be studied at 100 Hz without missing any event of the movement.

You can find examples of these systems of analysis in the market, such as Vicon https://www.vicon.com/software/nexus/; BTS Bioengineering https://www.btsbioengineering.com/products/smart-dx-motion-capture/; STT Systems https://www.stt-systems.com/motion-analysis/3d-optical-motion-capture/; Kinescan/IBV http://analisisbiomecanico.ibv.org/productos/tecnicas-de-registro/kinescan-ibv.html, Qualysis https://www.qualisys.com/software/qualisys-track-manager/; etc.

Parameters

The parameters drawn from the calculation of the **positions** and **orientation** of the segments and which are commonly used in kinematic analysis with these systems are: **relative angles** between segments and **absolute angles** in relation to the reference system, their **linear** and **angular speeds** and **accelerations**, as well as **distances** and **lengths.** The kinematic information combined with the information extracted from the force analysis also allows us to drawn parameters such as the external and internal **moments** that occur in the joints.

Advantages and disadvantages

The main advantages of these systems are their **accuracy** (remember that they are the current gold standard in movement analysis) and their **flexibility** to define models that analyse multiple segments and joints in 3D [5].

Some of the limitations of these systems lie in the fact that the markers may get **hidden** or **lost**, their **sensitivity to the environment lighting conditions** (such as changes in natural light outdoors), the **artifact** introduced by the markers placed on soft tissue like skin in dynamic movements, **errors** in the **placement** of the markers, the **time** needed to instrument them, or the **influence on the performance** of a movement because of the position of the markers in the body of the person assessed.

However, the constant evolution of these systems has reduced the problems related, for example, to the effects of light by introducing improvements to the sensor filters; or the effects of soft tissues through anatomical calibration procedures that also make it possible to remove some markers during the performance of the movements to be analysed [1].

Strict instrumentation protocols help improve the reliability of the results in studies where the measurements are performed on different days or by different examiners.

Equipment of 2D movement analysis

2D motion analysis systems are commonly used when the movement to be assessed is not complex and the relevant information occurs in a plane of movement, when the evaluation is performed in an outdoor or field environment, when the assessment does not require high precision in the variables extracted, etc.

These systems consist of a single camera, positioned towards the measuring space, and analysis software.

To ensure a correct position and angle of the camera, it is important to consider a number of factors such as the recording area, position of the camera in relation to the measurement plane, parameters of focal length and aperture of the camera sensor, recording speed, etc. The markers placed on the assessed person must be visible, as in traditional infrared capture systems, so that the system can track the markers throughout the recording.

The accuracy of this equipment depends on several factors, mainly those related to establishing references (control points) to **calibrate** the measurements and the distortions of the camera **lenses** to which the captured video images are subject.

The main source of error associated with the lenses is radial distortion. This distortion causes the well-known fisheye effect, which decreases precision when the reference lines are in the periphery of the image. To reduce this problem, a series of actions are proposed to improve the measurements:

- The reference lines should be on the same plane as the image.
- The plane where the movement is performed should be perpendicular to the camera axis (Figure 4).
- The identification of the reference segments and the segments to be measured should be located close to the centre of the image; similarly, the segments to be measured should be close to the reference segments.
- Do not make zoom or panoramic view adjustments to identify different segments.

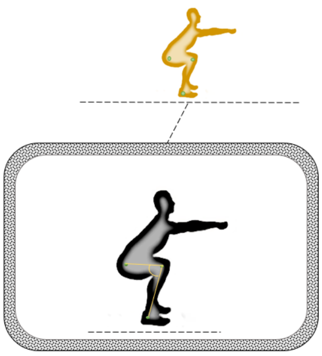

Figure 4 – Example of the perpendicular positioning of the camera in relation to the performance plane of a squat movement, located in the centre of the image.

Normally, the points associated with the markers instrumented in the subject are manually identified in the initial image of the movement studied. Some of these software programmes can track them automatically, establishing their position in the different sequences of the video to extract the related measurements. However, sequential manual recognition is also allowed in those cases where it is not advisable or possible to place markers in the person to be assessed.

There are some examples in the market of these analysis systems such as Kinovea https://www.kinovea.org/ or TEMPLO https://www.contemplas.com/motion_analysis_templo.aspx.

Parameters

The main study parameters extracted from these systems are estimated through the calculation of the position of the markers or segments defined and include **linear** and/or **angular speed** and **acceleration**, **distances**, **displacements**, and **relative** and **absolute angles** of segments or joints.

Advantages and disadvantages

The main advantages of this type of systems are: their **accessibility**, since they only need a camera, a tripod and a computer with the analysis software (which in many cases is free); their **portability**, as the assessments can be performed outside the laboratory; and the **information** they provide, especially in the analysis of simple movements that occur in a plane of motion, where relevant information can be extracted without the need for great precision.

With regard to their drawbacks, some factors affect the **reliability** and **precision** of the measurements obtained in the systems that are used outside a controlled environment, such as the influence of the examiner on the **instrumentation** and **assembly of the system**, the fact that breaking down a movement **in 2D planes** can lead to errors in angle measurements, problems associated with **lenses**, etc.

In summary, a 3D analysis system provides more precision and measurements in volume, but it is more expensive and complex; however, a 2D system has the advantage of portability (for example, for field tests) as well as being inexpensive and easy to use.

Equipment based on augmented reality (AR)

Augmented reality (AR) is a technique that uses artificial vision, image processing and graphic computing to add digital content to the physical world, providing interaction in real time [6], visualization, and handling of real and virtual objects.

This technique recognises marks or characteristics of the real image that are used as coordinates to superimpose or project virtual objects in 2D or 3D. AR can use objects or markers as reference markers or specific characteristics of the actual image to obtain this projection. Tracking rectangular reference markers is one of the most widely used tracking solutions for AR video applications [7] (Figure 5).

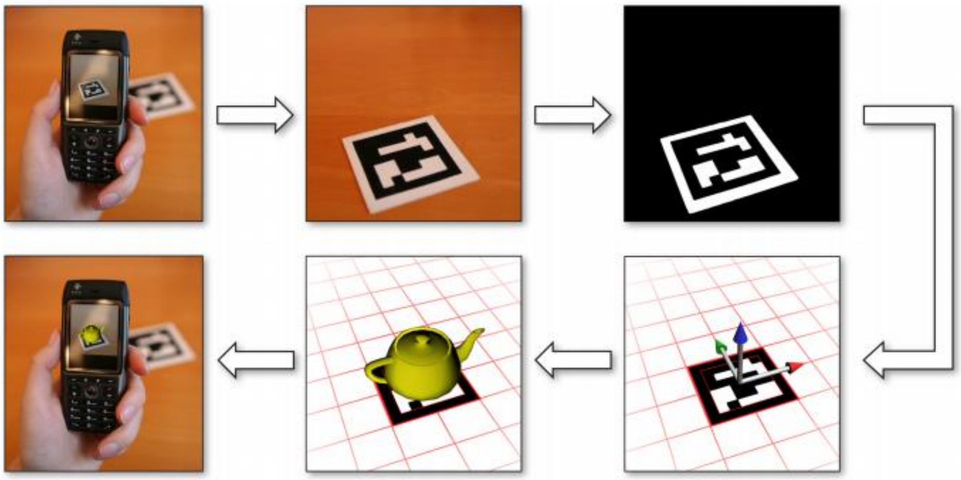

Figure 5 – Basic work diagram of an AR application (ARToolKitPlus) to detect and represent the pose of an object in 3D from a camera; image from Wagner et al. [7].

This technology is based on homography or projective geometry, which determines a correspondence between plane geometric figures and studies the relationships between three-dimensional figures in space and their projection on a plane. This principle is used by AR to identify the rotations and translations (3D kinematics) of an AR marker related to the camera's focus point and to the image plane based on the way the corners of the marker appear in the image recorded [8]. The main difference between AR and other processing systems is that, in AR, objects are rotated and moved in 3D coordinates instead of using a 2D image.

A simple AR system usually consists of a camera, a computational unit, and a screen [6]. It works by capturing the image with the camera, detecting the marker and inferring the location and orientation of the camera in order to project the virtual object on the real image and show the result.

The accuracy of these systems to estimate the location and orientation of the markers depends mainly on the calibration of the camera, which basically involves eliminating optical distortions and setting the resolution of the images and the size of the marker in pixels.

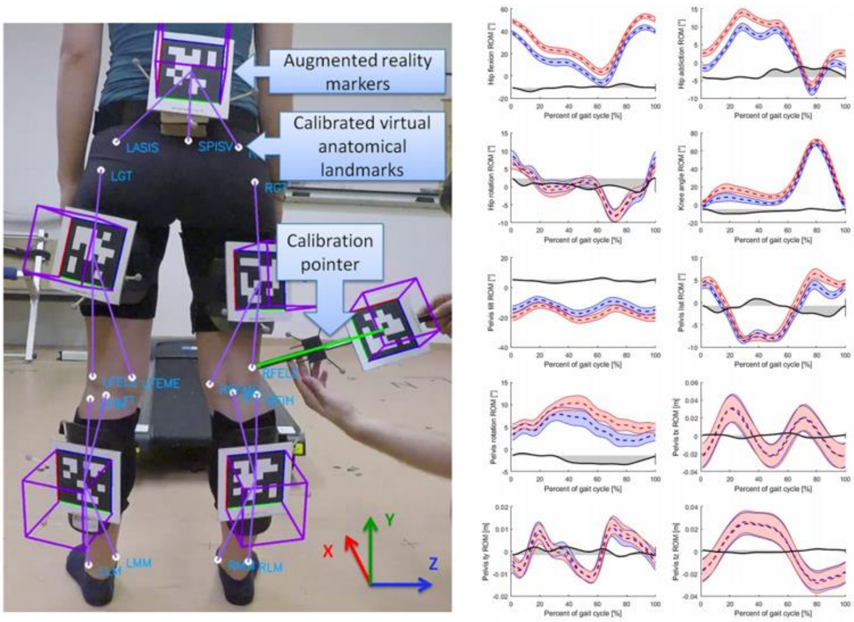

Figure 6 – Left: set of AR markers used to extract kinematic information of the lower limbs and comparison of the trajectories of the angles of the AR system (red) and of the Optitrack® movement analysis system (blue); right: images from Nagymáté et al. [8].

This equipment is mainly used in rehabilitation processes, due to the ability to interact with the user, or as motion capture systems. The study by Nagymáté et al. [8] proposes and validates an affordable gait analysis system compared to traditional 3D photogrammetry systems based on a single camera and a set of augmented reality (AR) markers. The AR markers are placed on the segments to be measured (Figure 6) ensuring that they are visible to the camera throughout the capture of the movement, in this case, the gait cycle. The results of the spatiotemporal and angular parameters of gait were compared with the results obtained using an optical system of 3D motion analysis.

Parameters

The main parameters provided by this equipment are extracted after obtaining the position and orientation of the segment to be assessed through the AR markers, as in the case of optical systems through the marker model that defines the segment. These parameters include the spatiotemporal parameters, joint range, speed, acceleration, etc.

Advantages and disadvantages

This technology makes it possible to interact with different environments or objects in real time in addition to recording kinematic variables associated with an activity, which facilitates objectives or tasks related to training or rehabilitation processes.

Tracking based on AR markers can work with a single camera, although motion capture may be limited to a single direction or in space so that the equipment's resolution can accurately process the image.

Marker-less systems

The current advances in movement assessment focus on the development of fully automated systems that do not use markers attached to the body. The computerized image processing of these systems reconstructs the movement from a video or an optical sensor, so that the subject does not have to wear any type of tracking marker [3]. This will improve research and healthcare practice in different areas such as the clinical setting and sports.

The most recent systems use stereographic cameras that imitate human binocular vision, or active cameras, which project light on the scene to create a depth map. These systems improve the efficiency of data acquisition compared to previous methods that used a set of synchronized and calibrated cameras, as well as a chromatic environment.

Figure 7. Image of the depth map using the OpenNI tool, from Dyce et al. [9].

A depth map (Figure 7) is an image in which the pixels describe the distance from a point in space to the camera, instead of the usual information about colour or brightness. Information about depth can help reduce the problems of traditional cameras: lighting conditions of the environment, shadows, reflections or uneven backgrounds [1].

In this motion capture equipment, the main thing is to recognise the silhouettes or structures that have to be located and tracked during the analysis. These systems adjust human body models to the silhouettes localized and extract the information about the segments studied. Then, such information is processed using reconstruction processes based on the model adjusted to the silhouette and the position of the object acquired from the image (generative algorithms), or processes that determine, through the automatic learning and training of the analysis system, the position of the model using only the image (discriminatory approaches).

The typical components of these marker-less motion capture systems are [1]: camera system, body model, recognition of the silhouette of the body or object, and the algorithms used to extract the parameters of the silhouette, posture and position of the body model.

One of the most widely used systems for entertainment is being increasingly applied in various fields such as rehabilitation, is the Kinect® camera by Microsoft. This camera generates a depth map by emitting infrared light on the body. Then, the Kinect® tracks the model adjusted on the image by combining information about depth and kinematics of the human body (Figure 8).

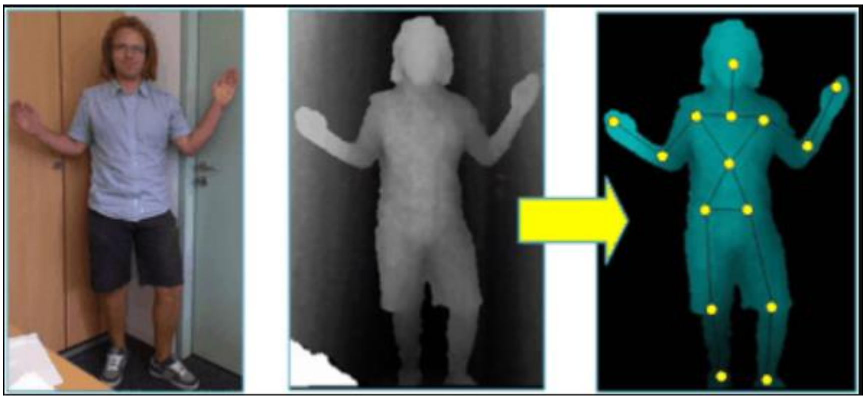

Figure 8. Images of Microsoft Kinect depth map and model generation, image extracted from Kristkler et al. [10].

In addition, there are more complex marker-less motion analysis systems that are specially applied to sports movements. They consist of several cameras that surround the area of analysis and body recognition software with which a body model is later associated for the calculation of kinematic variables in 3D (Figure 9). These systems can perform measurements both in the laboratory and outdoors as long as the lighting conditions and the colour contrast between the background and the object make it possible; however, this affects their precision and some planes of movement.

Figure 9 – Sports movement in real time, silhouette recognition and assignment of a body model, images extracted from Simi Shape 3D ® (http://www.simi.com/).

Currently, there are systems based on a single camera to extract 3D information. Following the adjustment processes of the movement plane and calibration, they track the body points that make up a predefined model through artificial intelligence methods composed of neural networks trained in identifying and predicting these points, as well as learning patterns based on the data received. The accuracy [11] in the range of motion variables obtained in some studies is sufficient to apply them in fields such as rehabilitation and sports training.

Parameters

The most common parameters extracted with these systems are analogous to those described for the marker-based systems.

Advantages and disadvantages

One of the main advantages of these systems is the ability to perform movement analyses in real environments, which saves the time needed to prepare the measurement when laboratory systems with marker instrumentation are used.

The resolution of the cameras used by these systems is normally 640x480 pixels, which may be adequate in the context of video games, but it can pose a problem when they are used to recognise specific body segments. In addition, the temporal resolution, which is around 30 Hz, limits their use to movements that are not performed at a high speed.

With regard to the accuracy of these systems, the studies included in the bibliography are mainly related to slow movements, such as human gait, whereas faster movements like those performed in sports remain to be studied; however, it should be noted that the accuracy and reliability of the results obtained in the study of rotations in the transverse plane are more difficult [1].

3. Inertial systems

Inertial systems are a type of non-optical systems based on inertial measurement units (IMU). In movement analysis, these units are usually made up of several sensors (Figure 10):

- **Accelerometer.** It measures acceleration forces, both static (such as gravity) and dynamic (generated by movement, shocks, etc.). The accelerometers used in these systems are usually triaxial, that is, they measure the **linear acceleration** that occurs in each of the three axes of space. In static movements (when the subject is not moving), they measure angular rotations.
- **Gyroscope.** It measures **angular speed**, that is, the speed of rotation of the sensor, in the three axes of space.
- **Magnetometer**. It allows us to know the **orientation** of the sensor in relation to the North magnetic pole, as well as the estimation of the position of the sensor together with the information from the previous sensors.

Figure 10 – Image of the sensors that make up an IMU, their size, and then commercially encapsulated, extracted from Xsens ®

The basic requirements to estimate the kinematics in 2D and 3D using this technology are [12]:

- Knowing the **orientation and position of the sensor** in a 2D and a 3D space. In isolation, the global position cannot be determined, only its spatial orientation. For this reason, this information is obtained by using fusion algorithms from the information of the sensors.
- Determining the **axes** where the movement occurs. The axes of the sensors must be **aligned** with the axes of movement of the anatomical reference system to facilitate the functional understanding of joint kinematics in 2D and 3D.

Calibration and **event estimation** procedures where a zero is used to correct the drift errors of the sensor are applied to solve the errors in the estimation of the position as a result of the calculations to integrate the signals from the sensors and to align the axes. These processes are usually performed *ad hoc* for the movement to be analysed.

Inertial sensors offer a precise and reliable measurement method to assess human movement, but their precision and reliability to estimate the necessary information varies and depends on the movement to be assessed because of the need to establish specific calculations. However, the improvement in the calculation processes makes them a valid system to study human movements [5].

The different commercial systems available in the market come in small and light boxes with wireless data transmission. These are attached to the body segment to estimate the movement of such segment in space [13]. In addition, two or more IMUs can be used to receive data from multiple segments simultaneously and synchronized, which generates a body model to estimate joint kinematics (Figure 11).

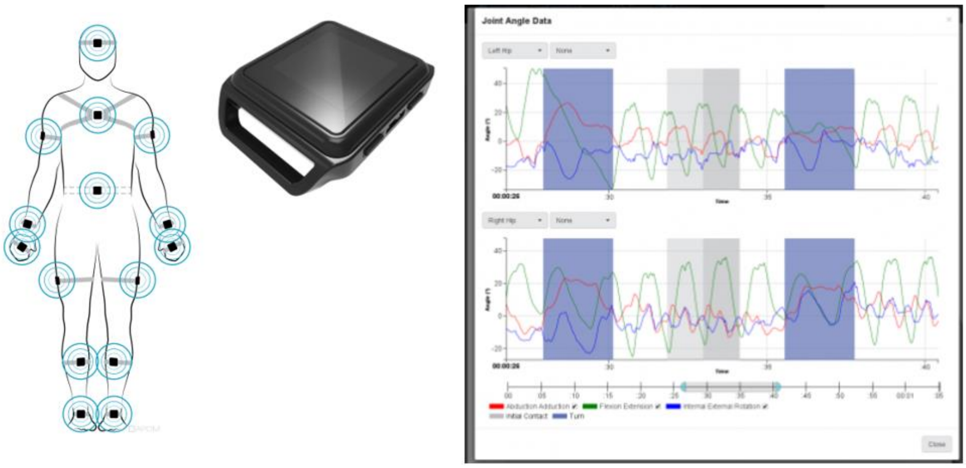

Figure 11 – Example of a model made up of Opal® inertial sensors and the results of joint angles by the Moveo Explorer® software, images extracted from https://www.apdm.com/kinematics/

There is a lot of literature about the use and usefulness of these systems; however, the identification of new solutions to increase their precision and reliability, as well as their applications, is still an open field with great expectations.

Parameters

The most common parameters calculated using a measuring system based on inertial units of movement are **linear accelerations** in the three axes of space, **angular velocities** in the three axes of space, **spatial orientation** (Figure 12), **relative angles** between two segments in the three planes of space, and **spatiotemporal events**, depending on the movement analysed.

Advantages and disadvantages

One of the main advantages of these systems is the ability to perform dynamic 3D analyses of human movement without the limitations or difficulties of optical systems. Characteristics such as their **portability** to be used outside the laboratory environment, **versatility** of use, and their price, make them an attractive alternative to traditional systems.

Their drawbacks include the susceptibility to **measurement errors** in the calculation of the **absolute position** due to the presence of metals in the measuring environment, the nature of the sensor, and the sensitivity of the data fusion algorithms to obtain the position by integrating the linear acceleration, which affects distance and length parameters. However, great progress continues to be made in this area to minimise these errors.

Another disadvantage of using inertial systems is the **instrumentation**, which limits the assessment of small joints or segments due to size problems.

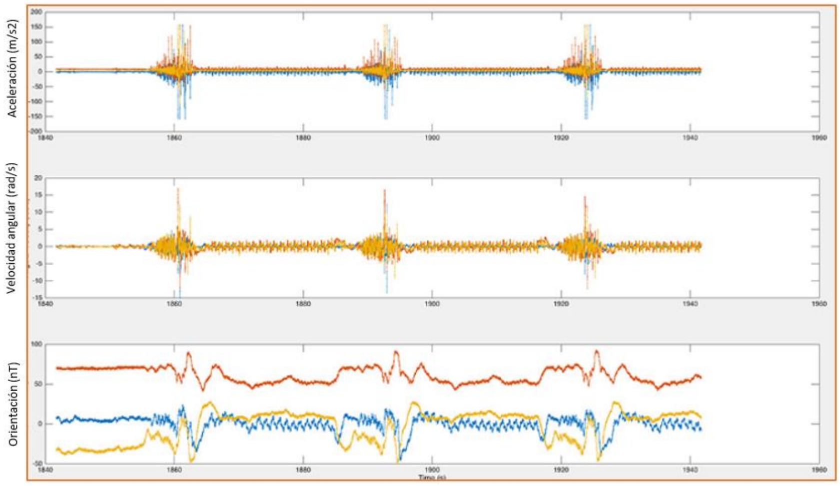

Figure 12 –Visualisation of the signals of the angular velocity, acceleration and orientation parameters coming from an inertial sensor; image extracted from imeasureu.com

4. Other

This section describes other systems for analysing movement that use different technologies from those described above, which are applied in various areas of biomechanical assessment.

Goniometer

Goniometers are passive devices commonly used in the clinical setting to measure joint angles, which is useful for objectifying mobility deficits as part of the clinical examination.

This instrument (Figure 13) is similar to an angle protector, but specifically designed to measure the joint angles of human body. There are different sizes and shapes depending on the joint to be assessed. The measurement is performed by aligning the axis of the goniometer with the axis of the joint to be measured, and each arm of the goniometer with the segments that make up the joint, then the angle measured is indicated [14].

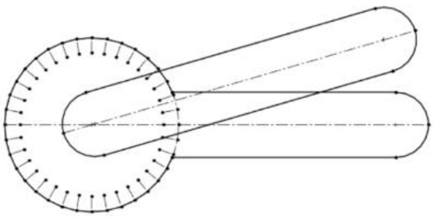

Figure 13 – Representation of a goniometer for measuring joint angles, image extracted from Christenson, J. [3].

Since the introduction of this instrument, various methodologies have been developed to describe how the measurements are performed and improve their reliability, since such reliability depends on the experience of the examiner to correctly position the goniometer, the joint and the person being assessed. The literature offers various publications about the reliability of the measurements performed by different examiners or the same examiner in different measuring sessions.

One of the most used methodologies is the one proposed by the American Academy of Orthopaedic Surgeons (AAOS). From its beginning in the 1960s until the last version from 1994, it has provided illustrations on how to perform the measurements from a specific "start zero position", but it does not show specific anatomical areas to align the goniometer arms, and the normative values provided are not accompanied with data on their reliability and in some cases are based on small examples with adults [15].

Different research groups have worked and continue to work on improving methodologies that use this instrument, providing recommendations for each joint based on reliability studies, as well as normative values segmented by age and gender.

Parameters

The parameter provided by the goniometer is the measurement of the articular **relative angle** between two segments, without providing the absolute position of the segment or of the joint in space.

Advantages and disadvantages

The main advantage of this instrument is that it is **inexpensive**, **easy to use** and **valid**, since it provides information on the joint angle, which is relevant in a clinical examination, for example.

One of the main disadvantages of goniometers, which is accepted in most contexts where it is used, is its **reliability**.

To obtain a continuous recording of this information during the measurement of a movement, **electrogoniometers** were developed. These instruments use a variable resistor or potentiometer and a mechanical attachment system so that the rotation of a joint becomes a turn of the potentiometer. This way, it is possible to directly obtain an electrical signal that is linearly proportional to the rotated angle. There is another type of electrogoniometers based on **strain gauges** (Figure 14), the instrumentation of which is much less cumbersome, and which measure angles in different planes depending on whether they are uniaxial, biaxial or triaxial.

Figure 14 – Example of a commercial wireless electrogoniometer system (Biomec®) used to measure the angle of the knee (blue) and ankle (red) in cycling.

Inclinometers

Inclinometers can be defined as instruments based on gravity which reference their measurements with respect to gravity, a zero start position, which they indicate by means of a weighted needle or a fluid (Figure 15).

Electronic inclinometers (Figure 15) are devices that use an **accelerometer** as a sensor element**.** This accelerometer uses the inertia of a mass located on a force sensor in order to measure gravitational acceleration. The change in the acceleration recorded by the sensor depends on the **inclination** of such sensor, recording a value in degrees.

Figure 15 – Baseline® Acu-Angle bubble inclinometer (left) and DTS 2d Noraxon® electronic inclinometer.

They are mainly used to assess the joint range of motion, recording the degree of deviation from the anatomical neutral position of the different segments of the lower/upper limbs, as well as the cervical, lumbar and thoracic spine. To do this, they are placed aligned with the body segments under study or anatomical landmarks such as the spinous processes or the occipital region by means of clamping straps (Figure 16).

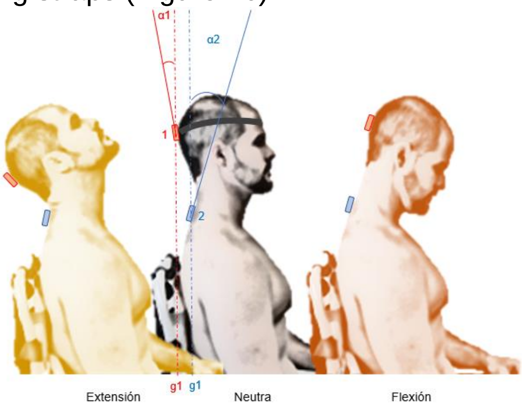

Figure 16 – Assessment of the cervical spine range of motion. The value of each position is extracted from the difference between the results of inclinometer 1 (red) and 2 (blue), modified image from NedRangos/IBV.

The information obtained from an accelerometer placed on the body or a body segment depends mainly on four factors: the position in which it is placed, the orientation of its location, the person's posture, and the activity that the person is going to perform [16].

Parameters

Inclinometers make it possible to record the angle measured with respect to the vertical (defined by the direction of gravity) or with respect to a reference position established, as well as the relative angles between the instrumented segments.

Advantages and disadvantages

The inclinometry technique is **easy to apply** in field conditions and causes minimum interference to the person who is performing the movement, especially in nearly static or slow measurements.

The main disadvantages of inclinometers are that it is not possible to identify the plane in which the deviation with respect to the vertical occurs (therefore, the sensors must be carefully aligned with respect to the measurement plane), and the fact that they cannot be used with rapid movements, since they are sensitive to acceleration.

GPS

The systems based in the location through the Global Navigation Satellite System (GNSS) are commonly called systems based on GPS technology (Global Positioning System). The development of these positioning systems is based on the atomic clock, which provides an accurate measurement of time, and allows us to know the time lapse between the transmission of a radio signal from the satellite and its reception by a GPS receiver system on Earth.

If the distance from the satellite to the GPS receiver is known, and there is communication with at least four satellites, the GPS receiver can be located by triangulation [17], as well as its direction and speed [18].

These systems are commonly used in open spaces, where there are no physical interferences that prevent correct communication, which causes errors in the accuracy of the location. However, the problems caused by the interferences of large constructions or specific atmospheric conditions are solved by differential GPS (DGPS) measurements, which use stationary receivers placed at ground locations to compare their fixed positions with the position given by the satellite [18]. Thus, for measurements performed in closed environments such as sports halls, there are systems with boosting equipment within the environment and/or which include inertial sensors in the receiving device itself.

The main elements that make up these systems are a signal transmitter/receiver in the subject's body, a signal repeater located at ground level, one or more satellites, or a local positioning system for closed environments or where communication is difficult (Figure 17).

In addition to the information drawn from the location, such as speed and distances, these systems usually include accelerometers that provide information on the intensity and the type of movement to be analysed.

The most advanced field of application of these systems is sports. The integration of the movement information transferred by these systems together with physiological, tactical or strategic data lends this technology great potential within sports.

Figure 17 – Communication elements of GPS receiver devices.

Parameters

The main parameters obtained from these systems are the **location** of the receiver (with an accuracy of centimetres or meters depending on the type of system), **direction**, **distance**, **speed,** and **acceleration** during the movement analysis, training or competition.

These systems may also contain accelerometers or inertial systems that can provide more accurate information on the movement: impact forces generated during the movement, accelerations that characterise the movement or basic spatiotemporal parameters such as the biomechanics of gait. Information on the exercise intensity can also be obtained by associating physiological information through heart rate acquisition.

Advantages and disadvantages

The main advantages of these systems are: they are **small**, **light** and **portable** devices that can be purchased at a reasonable price; above all, they do not interfere with the performance of the movements studied; they provide **free access** to communication with satellites around the world, which offers **contextualized information** for the environment and the activity being assessed.

The disadvantages of these systems include **low** communication **coverage** with the available set of satellites in some places, or the fact that the accuracy of the positioning of some systems is not adequate to measure specific activities.

5. Main areas of application

The instrumental techniques of kinematic analysis allow us to quantify human movement through the analysis of different variables. These variables are determined in the measuring procedures selected to characterise the object studied.

These methodologies for instrumented biomechanical analysis are frequently implemented and used on a day-to-day basis. This equipment is constantly being developed, and due to the improvements in portability and ease of use, this technology is being increasingly implemented, transferred from research laboratories to clinical consulting rooms, or even to the users themselves. However, it is important to correctly specify the technical characteristics of the equipment, as well as its procedures for use, reliability and validity with regard to the applications to which they are intended, which will avoid inappropriate use by professionals, teachers or end users.

The areas in which these techniques are usually applied are the clinical setting, sports and ergonomics. Some of the most common application cases in these areas are more specifically listed below.

Clinical setting

Within the clinical setting, the main applications and uses of these techniques are as follows:

- To characterise normal movements and movements that are characteristic of specific pathologies, both neurological and musculoskeletal.
- To objectively quantify the functional capacity of the person to perform activities of daily life and determine the degree of alteration.
- To plan the rehabilitation strategies, monitor their progress and adapt them.
- To help make decisions on whether to continue, modify or finish a treatment.
- To help implant and adapt orthoses and/or technical aids.
- To obtain indicators of the effect of a procedure in order to improve the efficiency of the current processes.
- To establish guidelines and to monitor by means of portable technologies that improve the adherence and motivation of people in specific health-related processes.

Sports

Within the sports field, the main applications and uses of these techniques are:

- To monitor the sports technique and improve the performance by quantitatively correcting errors and deficiencies in the technical movements.
- To support the professionals in their training techniques by assessing the assimilation of the training by the athlete.
- To identify the risk factors for specific injuries.
- To avoid injuries by advising on how to perform the sports techniques safely, based on the information provided by these techniques.

- To monitor the progress of various variables of interest in the sports rehabilitation process, which helps recovery and adaptation to sports practice.

Ergonomics

The main applications of instrumental techniques in the field of ergonomics in the workplace and product design are:

- Assessment/description of the musculoskeletal risk associated with a job.
- Characterisation of repetitive positions and joint movements involved in a specific job.
- Identification of behaviour patterns caused by muscle fatigue and loading in work-related tasks.
- Help in the redesign and validation of jobs and products.
- Assessment of devices and external aids in the work context.
- Product development under ergonomic criteria.

6. Examples

This section includes some examples of studies and applications intended for professional or user level, which use different instrumental techniques for motion analysis in line with the objectives described above.

In recent years, a significant increasing number of **clinical** research papers related to biomechanical analysis have been published, which shows an increasing interest in the differentiating information extracted from these techniques. This information is primarily applied in areas associated with the functional assessment of people's capacities, characterisation of various pathologies, establishing and planning a rehabilitation, etc.

The development of portable technology has contributed to the development of assessment equipment and systems for diagnosis that can be used by health professionals on an outpatient basis and are not limited to the biomechanical assessment laboratory.

Characterisation of pathologies

Human gait is one of the most studied activities at the clinical level. Instrumented studies of human gait analysis have been extensively developed to understand normal human gait and for the subsequent analysis of various pathologies that affect the musculoskeletal system.

The clinical analysis of gait allows us to extract information on the state, development and prognosis of some pathologies by analysing kinematic parameters that have a correlation with different functional aspects of gait. The specific characteristics of some alterations are reflected in certain parameters, both kinematic and kinetic, and studies are performed to determine their validity by comparing them with clinical scales or other functional tests.

For instance, the study by Weiss et al. [19] "Gait pattern in rheumatoid arthritis" analyses kinematic and dynamic parameters both in subjects with rheumatoid arthritis (RA) and in a control group to determine if there are parameters that determine levels of functionality associated with the Health Assessment Questionnaire (HAQ)-scores scale.

Subjects with RA may suffer alterations in the normal human gait pattern caused by joint degenerative changes, which leads to a functional alteration and changes in their quality of life.

The instrumental technique used for the kinematic recording is 3D photogrammetry with a Vicon Motion System® (Oxford, UK) analysis system made up of 6 cameras. The gait analysis model is Plug in Gait (PiG), provided by the Vicon® motion capture system. This model consists of 34 markers placed on anatomical landmarks of the head, trunk, arms, pelvis, legs and feet.

The most remarkable kinematic result of this study is the decrease in the articular range observed in the trunk, hip, knee and ankle (Figure 18). In addition, a correlation of some kinematic parameters is observed in the results extracted from the HAQ. These studies can be useful to help understand how RA affects gait changes in the lower limbs.

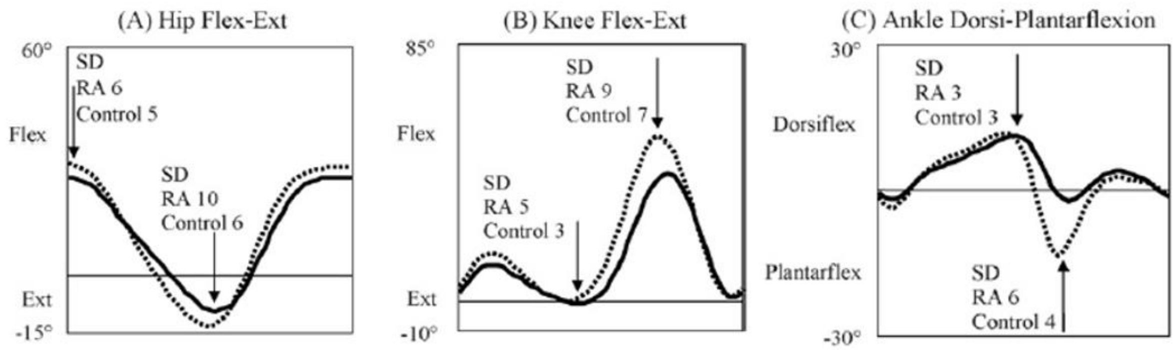

Figure 18 - Kinematics of the RA group and the control group. Flexion/extension angles of the hip (A) and knee (B), and dorsal/plantar flexion of the ankle (C) during the gait cycle. Solid line (-): control group, dashed line: (- -) RA group. The standard deviation (SD) is shown for all the maximum parameters; extracted from Weiss et al. [19].

Functional assessment

Falls are one of the current problems of the population over 65 years of age. It is estimated that one out of three older adults fall each year, which is the second world cause of accidental or unintentional death. Falls imply a deterioration in the autonomy of elderly people, reducing their quality of life. Traditional tools to assess the risk of falling have some limitations such as subjectivity, in the case of functional scales, or the fact that they are time-consuming for use in daily clinical practice, in more comprehensive tests.

Tools based on instrumental techniques are currently being developed to provide solutions tailored to the needs of healthcare professionals. As an example, the FallSkip system uses the inertial sensors of a mobile device to collect information during the performance of a simple set of tests in a clinical setting. This test (Figure 19), based on a modified protocol of the Time Up and Go (TUG) test, collects specific parameters related to gait, balance, motor control and muscle strength. These parameters are related to the assessment of the risk of falling in older people.

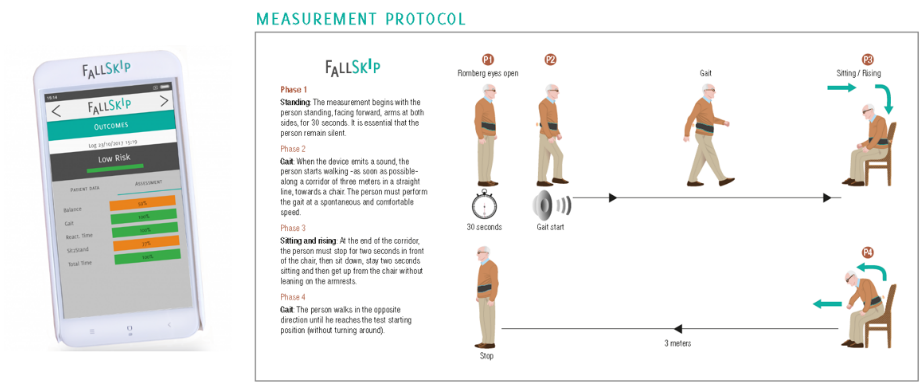

Figure 19 – Mobile device and measurement protocol of the FallSkip system; images extracted from http://fallskip.com/

This is intended to streamline and simplify the extraction of differentiating objective information of interest based on biomechanical variables that allows us to know the functional state of a person regarding their risk of falling.

The applications in the field of **sports** are more popular in terms of impact and demand mainly due to the increasing number of people who do sport and participate in different disciplines related to health promotion policies through physical activity.

Instrumental techniques of biomechanical analysis make it possible to extract quantitative information related to training techniques, selection of training material or the monitoring of variables related to performance and health protection [20].

Selection of sporting equipment

An example of the research results on the kinematic analysis of running and footwear selection is the development of tools such as the Runalytics® system by the Instituto de Biomecánica of Valencia (IBV). This system performs a real-time analysis of the joint angles of the foot during the stance of the running gait and classifies them according to the type of footprint (pronator, supinator, neutral) using classifiers based on data management techniques and machine learning. This system uses an analysis technique based on video images together with augmented reality markers located in the runner's leg and hindfoot, which makes it possible to measure the relative movement in the space of the leg and foot body segments in 3D (Figure 20). This analysis allows us to advise on the type of footprint when running and to select the most suitable footwear.

Figure 20 – Runalytics© system for the analysis of the footprint when running; images extracted from http://www.runalytics.es/

Assessment of sports techniques

The technical assessment of athletes is an essential process to evaluate the individual efficiency and adaptation to a sporting discipline. This assessment allows us to know the athlete's capabilities and to lay the foundations for the subsequent planning and intervention in the training process. Nowadays, the constant improvements in the different aspects of the athlete's preparation, such as nutrition, physical condition, etc., make the objective and accurate assessment of sports technique a differentiating factor to achieve better results.

One of the objectives of the evaluation of sports techniques is to analyse the variables that occur in the different key events during the performance of the sports movement in order to detect deficiencies, opportunities for improvement and/or training effects. Traditionally, this type of assessment was performed by coaches through direct observation, which is a simple and fast method, but requires experience and knowledge on the part of the examiner. The introduction of instrumental techniques provides an objective record of the specific quantifiable parameters of the movement or discipline to be analysed. Currently, portable and non-invasive systems make it possible to perform this type of assessment within the sports context, providing realism and validity, whereas laboratory assessments offer advantages such as objectivity, standardisation and reliability [21].

In the case of tennis, two examples of the use of instrumental techniques for kinematic analysis are included below. Both examples focus on the analysis of sports technique.

The paper by Ebner and Findling [21] “Tennis Stroke Classification: Comparing Wrist and Racket as IMU Sensor Position” studies a methodology to detect and classify 8 strokes that occur in tennis, and to visualise the differences in the angular velocities and accelerations in 3D extracted from the information provided by two inertial sensors: one located in the racket and another in the player's wrist (Figure 21).

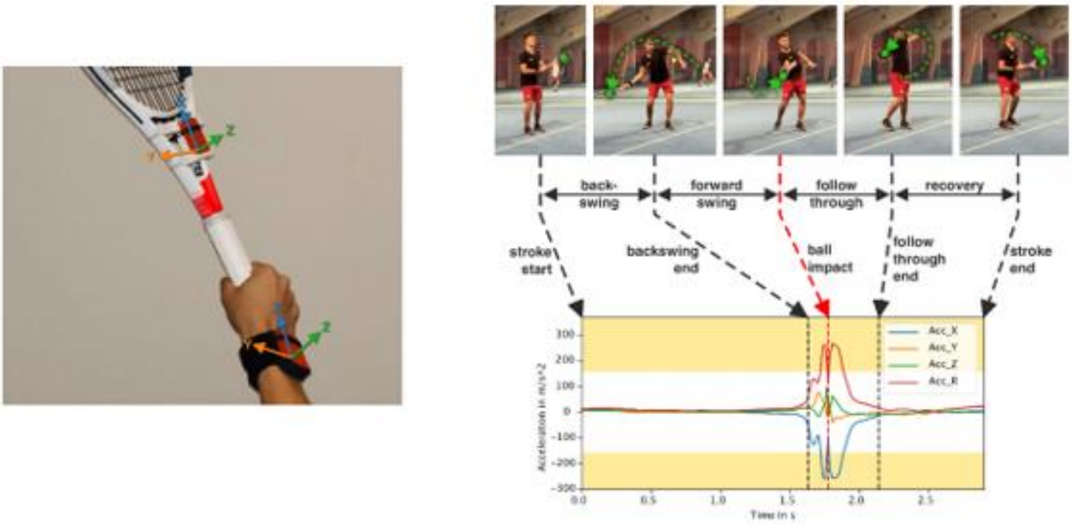

Figure 21 – Mounting of inertial sensors in the racket and the wrist (left), and example of the accelerations recorded in the different phases of a stroke (right); images extracted from Ebner y Findling [22].

The work by Yang et al. [23] “TennisMaster: an IMU-based online serve performance evaluation system” presents a system for assessing the performance of the serve movement when training. The information is also extracted from two inertial units located in the player's tibia and wrist (Figure 22).

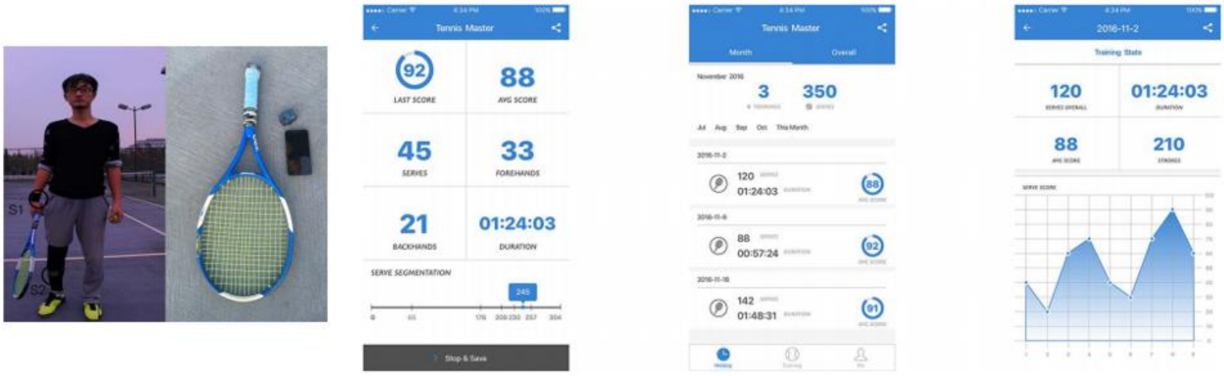

Figure 22 – Mounting of inertial sensors (S1) on the bottom of the racket (S2), and in the tibia of the player (left). Examples of the app screenshots showing the serve score, number of strokes, training history, etc. (right). Images extracted from Yang et al. [23].

These systems make it possible to quantify the loading carried out by the player and the performance level, which helps the coach to approach and plan the training, as well as the player by giving them feedback on the training.

In the field of **ergonomics**, the use of instrumental techniques to record joint mobility, the position of different body segments, the reaches and task performance, makes it possible to research, study and develop methodologies for the correct adaptation of environments and products. Within the work context, it is important to record and quantify variables related to the mobility and position of specific body segments in specific tasks of the job. This information allows us to determine, for instance, the risk of musculoskeletal disorders by assessing the job risk through methodologies based on the analysis of awkward posture, repetitive movements, etc.

In this regard, two studies related to ergonomics in the workplace are shown as an example of application.

Characterisation of working tasks

Repetitive movements are frequent in many jobs and can lead to musculoskeletal problems in the upper limbs. The work by McDonald et al. [24] “Muscular and kinematic adaptations to fatiguing repetitive upper extremity work” includes a study on the occurrence of fatigue in specific tasks that involve the upper limbs as well as on the changes in the kinematics of the patterns over time.

The instrumental technique used for the motion analysis is the Raptor-4 system by Motion Analysis Corporation, Santa Rosa, (CA). Eleven cameras recorded at a frequency of 50 Hz and a model of 72 reflective markers were used to obtain the 3D angles of the joints of the wrist, elbow, shoulder and trunk. To simulate these tasks, a workstation designed in the movement laboratory was used together with other instrumental techniques such as surface electromyography and a force platform (Figure 23).

One of the main conclusions of the study is that muscular adaptations and kinematic patterns are task and time dependent. (Figure 23). These studies can help to further study the postural changes that certain tasks involve, depending on the load and the performance time, and thus provide solutions and strategies to minimise possible musculoskeletal risks.

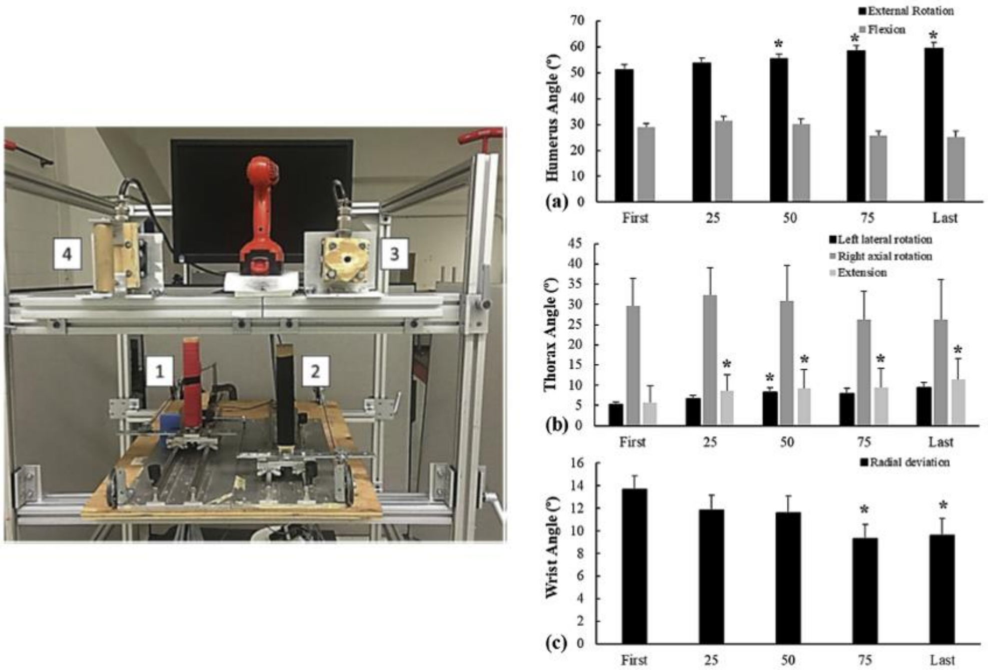

Figure 23 – Workstation with four tasks: (1) pull task, (2) push task, (3) drill task and (4) up/down target task with 2 force levels (left). Angle differences in different joints over time during the drill task (right). Images extracted from McDonald et al. [24]

Assessment of external aid devices

Awkward posture, or activities involving carrying and lifting loads are common tasks in certain jobs, especially in the industrial sector. In addition, lumbar spine disorders are one of the most prevalent disorders in today's society. Thus, interventions related to the ergonomic adaptation of tools and workstations have been performed in the working environment of the industrial sector; similarly, devices that help in load handling tasks have been developed to minimise the risk of injury to the lumbar spine or the upper limbs. One of the newest devices that are currently used are exoskeletons. These systems can be either active, containing actuators that assist the subject, or passive, whose main objective is to support and unload through different elements such as springs, shock absorbers or materials with the ability to store energy and return it to the subject at the necessary time.

The work by Picchiotti et al. [25] “Impact of two postural assist exoskeletons on biomechanical loading of the lumbar spine” studies the behaviour of two different models of exoskeletons (Figure 24) by analysing kinematic variables, as well as muscle activity and strength, also introduced in this study.

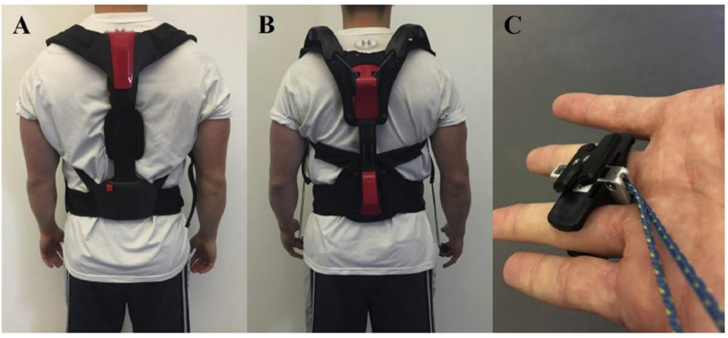

Figure 24 – images of the exoskeletons tested in the study: the FLx (A), V22 (B) and the hand actuator of the V22, images extracted from Picchiotti et al. [25].

The instrumental technique used for movement analysis is an optical motion capture system made up of 42 Prime 41 OptiTrack cameras (Natural Point, Corvallis, OR, USA) with a full-body model consisting of 41 markers whose location in the body is determined by the OptiTrack motion capture software. The recording frequency is performed at 120 Hz.

This study compares the results of the flexion angles in the joints of the trunk, hip and knee segments during lifting tasks with the two exoskeletons and a control condition (Figure 25). Additionally, the moments at L5/S1 joint level and the biomechanical loading of the lumbar spine tissues were calculated using dynamic information.

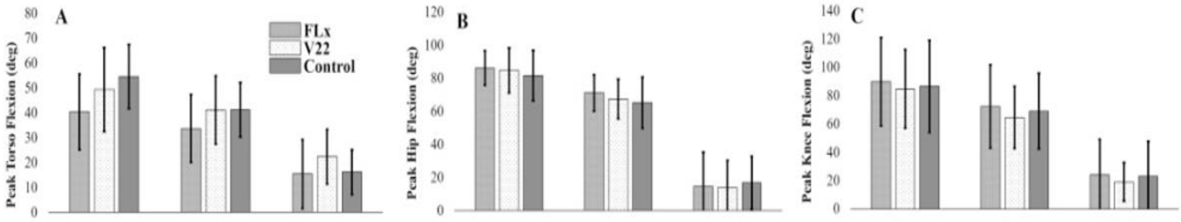

Figure 25 – Differences in peak knee flexion between the two exoskeletons assessed and the control condition at trunk (A), hip (B) and knee (C) level; images extracted from Picchiotti et al. [25].

These studies help to understand how these devices can help improve posture during the performance of some tasks and the relation or influence with respect to the variation in the load of the lumbar area (in the case of this study) or other segments, such as the upper limbs in exoskeletons designed for this purpose.

7. Key ideas

The key ideas of this didactic unit are:

- There are different techniques of movement analysis.
- The main techniques are based on the analysis of images or signals from other sensors such as accelerometers, gyroscopes, etc.
- The main parameters extracted from these techniques are related to position, joint range, acceleration and speed.
- It is necessary to know the technical characteristics and specifications of the different techniques, as well as their measuring procedures so as to select the technique according to the object to be measured.
- Instrumental techniques of biomechanical analysis are implemented in areas such as clinical setting, sports and ergonomics with multiple applications.
- The constant technological development, such as portable recording systems connected to mobile apps, will allow new applications for biomechanical assessment to be developed and expand the scope of application.

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