MODULE 2: BIOMECHANICS IN STROKE REHABILITATION

Session 1: INTRODUCTION TO BIOMECHANICS. CLINICAL BASIS AND USEFULNESS IN THE REHABILITATION FIELD

Index

1. OBJECTIVES OF THE SESSION

At the conclusion of this session, the student should be able to:

- Define biomechanics and its main applications.
- Study the relationship between biomechanics and functional assessment.
- Identify the differences between assessment based on direct observation and instrumental techniques.
- Describe the main instrumental techniques, their classification and main characteristics.
- Discuss the main results obtained using different instrumental techniques.
- Explain the main advantages and limitations of each instrumental technique.
- Review the main applications of biomechanical assessment in various fields and in stroke rehabilitation.

2. INTRODUCTION TO BIOMECHANICS

2.1. Definition of biomechanics

Generally, biomechanics allows us to explain the mechanisms of life and makes us more aware of it. It is a useful, simple, valuable and inevitable tool that makes it possible to design and invent systems to improve our quality of life.[1]

From the point of view of this session, **biomechanics** can more precisely be defined as the study of biological systems using tools from mechanics. Biomechanics covers the study of human body from a mechanical perspective, although it is not limited to it.

Mechanics is the branch of physics that studies the behaviour of bodies subjected to the action of forces and is traditionally divided into three parts. **Kinematics** analyses and describes movement and therefore studies variables such as angles, positions, speeds, angular velocities or accelerations; **dynamics** studies the causes of movement and analyses forces and moments, and **statics** is concerned with the analysis of bodies at rest.

In the case of human beings, movement represents the distribution of forces in the joints in time and space. These forces are of different types: applied internal forces (generated by the muscles), internal compression forces (body weight) and external forces.[2]

Biomechanical research deals with interrelated mechanical and non-mechanical influences of the locomotor system.[3] In fact, biomechanics can be conceived as **multidisciplinary knowledge** since it draws on knowledge from other disciplines such as physics, metrology, computer science, statistics, clinical and theoretical medicine, etc. Thus, one of the most current definitions of the concept of biomechanics was provided by the Instituto de

Biomecánica of Valencia (IBV) in 1992 as a set of interdisciplinary knowledge generated from using—with the support of other biomedical sciences—the knowledge of mechanics and different technologies for studying the behaviour of biological systems, specifically human body, and for solving problems caused by the different conditions to which human body may be subjected.

2.2. Main applications of biomechanics

The applications of biomechanics may vary depending on the field where it is applied. This session includes some of the main applications in the areas where it is most widely used, such as the clinical setting, sports and ergonomics.

Clinical setting

The main applications in the clinical field include:

- To objectively know the patient's ability to perform activities of daily living.
- To characterise and identify certain pathologies, both neurological and musculoskeletal.
- To provide information about the progress, planning and appropriateness of the treatments.
- To help to decide whether to continue, modify or end a treatment.
- To help to implant and adapt orthoses and/or technical aids.
- To determine prevention actions in specific pathologies.

Sports

The main applications in the sports field include:

- To assess the sports technique and performance improvement by quantitatively analysing technical movements.
- To provide support to athletes in their training techniques by assessing their training assimilation.
- To prevent injuries based on the information provided by certain study variables.
- To provide information on the progress of the sports rehabilitation process.

Ergonomics

The main applications in the ergonomics field include:

- To assess and describe the musculoskeletal risk associated with a workstation.
- To characterise the repetitive positions and forced movements that a particular workstation involves.
- To assist in the redesign and validation of workstations.
- To recommend guidelines of active ergonomics.

3. FUNCTIONAL ASSESSMENT AND BIOMECHANICS

3.1 An approach to functional assessment

The clinical history is used to collect information in a systematic way and to establish the diagnosis of a specific pathology or disorder. A clinical history is structured in several parts such as anamnesis, physical examination and complementary tests, which are often necessary to confirm the diagnostic suspicion after performing the anamnesis and the physical examination.[4] These tests (for example, radiodiagnosis tests) provide quantitative and objective information, but the relationship between this information and the functionality expressed and/or shown by a patient is limited.

The term **functionality** refers to what people do or how they do it; activities, tasks, skills or abilities that individuals need to adapt to the environment: activities of daily living (ADLs), personal care, mobility or communication, among others. These capacities are included in the assessment of the function or structure of the body, activities and participation, as components of the function and disability based on the International Classification of Functioning, Disability and Health (ICF).[5]

Functional assessment stems from the need of physical medicine and rehabilitation to evaluate their results,[6] since the ultimate goal of the treatments proposed is to reach the highest level of functional capacity or ability. Both from the clinical and managerial perspective, it is worth highlighting the results regarding the effectiveness of the treatment, the patient's progress, and the planning of the needs of their services.

Functional assessment is the object of measurement of functional evaluation and includes the methods, instruments and tools used to measure the functionality of people.

The most common instruments to measure function are the **clinical scales** and **instrumental techniques** used in biomechanical assessment.

3.2 Clinical scales vs Instrumental techniques

In general, every measurement system has the following characteristics:

- Maximum and minimum limits. Maximum and minimum values that can be recorded by the equipment.
- Range. Difference between the maximum and minimum value that a device can record.
- Sensitivity. Minimum variation of the variable studied that the device can detect.
- Resolution. Smallest exact measurement that can be performed with the instrument. It is the minimum increment of the variable that can be quantified with the device. For example, the resolution of a 10-cm ruler divided in millimetres is 1 mm.
- Precision. Ability of a measuring instrument to give the same value of the measured quantity, when performing several measurements under the same specific conditions, without considering their consistency or discrepancy with respect to the real value of such quantity. This term is also known as repeatability.

- Accuracy. The ability of an instrument to give values that approximate the true value of the measured quantity.
- Validity. Criterion that refers to the fact that the measuring instrument measures exactly what it is intended to measure. Studies on the validity of a measuring instrument must always compare it with a reference standard or "gold standard" whose validity has been previously proved.

The following table graphically shows some of these concepts to facilitate understanding.

Precision, no accuracy	**Accuracy, no precision.**
	
No precision, no accuracy	**Precision and accuracy**
	

Table 1. Examples of the concepts of precision and accuracy

Clinical scales

Clinical scales are a source of clinical information, most from the patients themselves, that is obtained through standardised questionnaires. There are different clinical scales according to:

- Object of measurement. Some scales are concerned with the different domains of a person in a given medical condition. Some of them deal with bodily functions such as muscle strength, others assess activities like gait, and finally, some evaluate participation, considering how a disorder affects personal development.
- Aspects assessed. Some scales deal with a single aspect, whereas others group different tasks or functions.
- Results provided. Some classify the function or activity in different levels, while others provide a percentage associated with a degree of functionality or even risk.
- Administration time. Some take only a few minutes while others require much longer.
- Technical training required. The application of some scales requires previous training or specific knowledge; others are self-explanatory and self-administered and can be applied by unqualified personnel.

The information obtained from these questionnaires, for example, can help detect disorders, can be used to monitor the evolution and progress of a patient, establish population references, assess the effectiveness of a specific treatment, etc.

However, there are barriers concerning practice and attitude in the effective use of instruments based on information reported by patients for its application in clinical practice.[7] For example, such instruments tend to be subjective, both from the point of view of the patient and the evaluator who observes and qualifies the items; they are limited in terms of resolution and sensitivity;[8] moreover, many questionnaires are often long, and both patient and evaluators find them cumbersome.[9]

Cross-cultural adaptation to populations with socio-cultural differences with respect to the context where the scales were created is an additional limitation, but necessary to maintain the validity of the content of the scale, as well as to avoid variations in its sensitivity and specificity.[10] Thus, using a validated questionnaire in a language or environment different from that in which it was developed requires a reproducible method.[11] Validating a questionnaire in a language other than the one it was created in implies two stages: a first stage of translation or cultural translation, and a second stage to validate this translation made in the country for which it is intended.[12]

Instrumental techniques

Instrumental techniques of biomechanical assessment are instruments that provide objective and quantitative information which can be applied in the assessment of a function or body structure, activities and participation.

The instrumental techniques used in biomechanical assessment are a fundamental tool in functional assessment because:

- Biomechanics is concerned with the study of all biological phenomena and with human body in particular.
- Mechanics, with great technological support, has its own methods (more or less peculiar) that can be applied to study living beings.
- Biomechanics developed because it provides a useful approach to study and solve problems that affect human beings, otherwise we would not be dealing with it with such interest.
- Biomechanics is interdisciplinary and, therefore, it is necessary to master different branches of science.

Functional assessment using instrumental techniques uses a procedure to prepare the assessment, to perform the assessment itself and to analyse and interpret the results. The stages that make up this procedure are broadly described below:

Stage 1. Preparation of the assessment

- Identifying the phenomenon to be studied and the boundary conditions. We must identify what we want to measure and accurately determine the aspects to be assessed and the conditioning factors in the assessment, which can include the place where the assessment is performed, the budget or the human resources available.
- Selecting the appropriate measurement technique taking into account the object of study and the conditioning factors. Making a correct choice requires sufficient knowledge about instrumental techniques.

- Preparing the equipment. Some measurement systems require calibration, establishing a synchronisation system among devices and/or previous training to operate them.
- Defining the assessment protocol. The protocol must be perfectly established. It is very important to define in great detail the protocol and how it will be performed. It is especially advisable to carry out a pilot test of the procedure established in order to verify the feasibility and validity. Currently, commercial equipment often includes a well-established assessment protocol so that users only need training to apply it correctly, but they do not have to define it.

Stage 2. Performing the assessment

The assessment should be performed according to the protocol established in the previous phase. It is important to apply the protocol very strictly in order to ensure that it meets the objective set. It is also advisable to verify that there have been no errors when recording or executing the protocol to meet the objective previously established.

Stage 3. Analysis and interpretation of the results

Some instrumental techniques provide the desired information as a result of the assessment, but in many cases, instrumental techniques entail a number of previous steps to analyse and interpret the results, such as signal processing, definition of the variables or the parameters of the study, and statistical treatment for analysis.

Main differences

Both clinical scales and instrumental techniques are useful in the assessment of function, but there are fundamental differences that must be taken into account when deciding which technique or combination of both to use.

The following table describes the fundamental differences:

Clinical scales	Instrumental methods
Subjectivity	Objectivity
Limited sensitivity to changes	High sensitivity to changes
Significant ceiling effect	Significant floor effect
Need no equipment or other infrastructure	Need equipment and other infrastructure

Table 2. Main differences between clinical scales and instrumental techniques

An example of a clinical scale and an instrumental technique for assessing balance function is included below.

Berg clinical scale

It provides a quantitative assessment of static and dynamic balance based on the assessment of fourteen items related to activities of daily living. The patient is asked to maintain determined positions or complete tasks with different levels of difficulty. Each item is scored on an ordinal scale of five points that goes from zero to four, where zero is the lowest level of capacity and four represents the highest level.

The minimum score is zero, whereas the maximum score is fifty-six; the score obtained indicates the risk of falling:

>41 = low   21-40 = medium   <20 = high

Applying this scale takes approximately ten minutes, requires little training, offers excellent repeatability, validity and sensitivity to change and it is widely used in the clinical setting.

Computerised dynamic posturography

Computerized dynamic posturography (CDP) is a technique for assessing postural control that records the projection of the centre of gravity while the patient performs different tests in the standing position (Image 1). It provides objective and quantitative information on the contribution of the different systems involved in the maintenance of balance (visual, somatosensory and vestibular system). CDP assesses balance under dynamic conditions and during the displacement of the centre of gravity in different directions.

Image 1. The subject stands on a force recording platform during the Romberg test with eyes open (left),eyes closed (centre) and on foam with open eyes (right).

The aspects explained during the session about the two assessment methods selected are compared in the table below:

	Berg Scale	Computerised dynamic posturography
Objectivity	Subjective measurements	Objective and quantitative measurements with high precision and reliability.
Sensitivity to change	Low sensitivity	High sensitivity

Ceiling/floor effect	Ceiling effect	Floor effect, no ceiling effect
Equipment and other infrastructure	Little experience required and no infrastructure	It requires posturography equipment, space and a trained evaluator to operate and it interpret the results.
Duration	10 minutes	20 minutes
Other considerations regarding usefulness	Useful to assess the risk of falls. Its validity has been proven.	Useful to assess the risk of falls, control patient progress and provide a functional diagnosis of postural control. Its validity has been proven.

Table 3. Results of the different characteristics of both methods of assessment for balance function: Berg scale and computerised dynamic posturography.

Selection criteria

It is important to bear in mind that, in addition to the general differences exposed, each tool has its own properties in terms of validity, repeatability or ease of administration. Functional assessment needs instruments that are repeatable, valid and sensitive to change. Therefore, it is important to know the appropriate selection criteria to choose the right instruments such as **repeatability**, **validity**, **sensitivity to change** or the administration **cost** in terms of **time and resources**, which are properties of the measurement instruments that can affect the credibility of the measuring process and the results of a research.

The evaluator must know the instruments available and these properties in order to select the appropriate instrument for each case.

In addition to repeatability, validity and sensitivity to change, it is useful to consider two additional questions when selecting a measurement technique for human functions.

- The measurement should have proved to be useful to assess a function in a population comparable to the population under study. Otherwise, it will be necessary to verify its usefulness.
- At which moment it is advisable to perform the measurement.

Advantages and disadvantages

The **advantages** of functional assessment using instrumental techniques over clinical scales are:

- Objectivity of the measurements. Clinical scales are usually based on subjective criteria, while instrumental techniques provide objective information.
- High sensitivity to detect changes in a functional status. A change in the functional status of a person can only be detected by a scale when the improvement is very significant,

since scales are not usually very sensitive to small changes; however, instrumental techniques are sensitive to small changes.

- There is no ceiling effect. Clinical scales usually reach their limit when the person or aspect being assessed has an acceptable functionality, but they are not sensitive to improvements in the functional status when this level has already been reached. Instrumental techniques can record differences even when the functional level according to clinical scales has already reached the maximum.

Nevertheless, they also have a series of drawbacks:

- Floor effect. The minimum functional level required to perform a functional assessment using instrumental techniques is usually higher than that required for clinical scales.
- They need equipment, space and appropriate conditions to perform the assessments.
- The staff who will use these techniques has to be previously trained.

Moreover, there are **difficulties** associated with the use of instrumental techniques for functional assessment that the evaluator should consider and control. The most noteworthy are related to:

- Heterogeneity of the assessment protocols and means used. The differences among the different protocols are remarkable regarding aspects such as the measurement technique/s or instruments used, movement or aspect to be assessed, algorithms used to calculate variables, variables analysed, information analysis strategies, etc.
- Aspects that may affect the repeatability and reliability of the measurements: characteristics of the measurement technique, condition of the equipment, or the repeatability of the measurement protocol used (instrumentation, instructions to the subject, training and experience of the evaluator, characteristics of the person being assessed, standardisation of the movement to be assessed, etc.).
- Instrumental techniques not adapted to the clinical setting or to functional assessment: some measuring equipment used to evaluate functions was developed without considering the user profile for whom they are intended. Such equipment must consider, at least, the usability for professionals of the health sector, automatic data processing, incorporated measurement protocols whose validity and repeatability have been previously proved, incorporated assessment criteria (reference values or databases), reliable and valid assessment systems through relevant studies, etc.

Biomechanical assessment is being increasingly used to objectify the functional impact of a pathology or physical disorder on the rehabilitation field by applying instrumental techniques and measurement procedures.

Finally, as previously mentioned, both methods are useful for functional assessment; however, before selecting these assessment methods, it is necessary to know what is going to be assessed, what is to be measured, with what objective, the effort involved, and to make a correct interpretation of the results obtained. All this involves comprehending the advantages, disadvantages and limitations[13] prior to choosing an assessment technique or a combination of both.

4. CLASSIFICATION OF THE INSTRUMENTAL TECHNIQUES OF BIOMECHANICAL ASSESSMENT

The instrumental techniques applied in the assessment of human functions can be classified according to different criteria. In this session, they are classified according to their object of measurement:

4.1 Instrumental techniques for the analysis of force

Concept and classification

Force analysis is one of the objects of study of biomechanical assessment, providing very relevant data on many human functions.

This session explains the main instrumental techniques of force analysis applied in functional assessment, along with the concepts of interest to understand how they work and to interpret their results.

The instrumental techniques of force analysis can be classified in different ways; however, this session classifies them according to what they assessed: muscle strength, reaction forces and pressures.

Physical quantities and variables of interest

This section intends to provide the foundations of the relevant physical quantities applied in the study of the forces that produce movement and motion or kinematics variables.

The main variables related to the study of forces are described below:

ACCELERATION

Acceleration is the change in velocity per unit of time, which determines if the object under study increases its speed (positive acceleration) or reduces its speed (negative acceleration or deceleration). Acceleration is expressed in the International System of Units (SI) in m/s^2 (meters per second squared).

FORCE

One of the most important quantities within mechanics will be defined below: force. According to the classic definition, force is any action or influence than can modify the state of motion or rest of a body, that is, to introduce acceleration by modifying its speed. The formula is:

Force = Mass * Acceleration

The fundamental unit of force, according to the International System Units (SI), is the newton (N), which is defined as the force needed to accelerate 1 kg of mass at a rate of 1 m/s^2.

The unit of force in the old gravitational metric system is the kilogram-force. Based on the previous formula, 1 kilopond (kp) or kilogram-force (kg_f) equals 9.80665 N according to the gravitational constant of the Earth.

$$1kg_f = 1kg * 9.80665m/s^2 = 1N$$

Forces are vector quantities because, in order to determine them, we do not only need to know their value (modulus), but also their magnitude and direction. Therefore, they will be represented and treated as vectors.

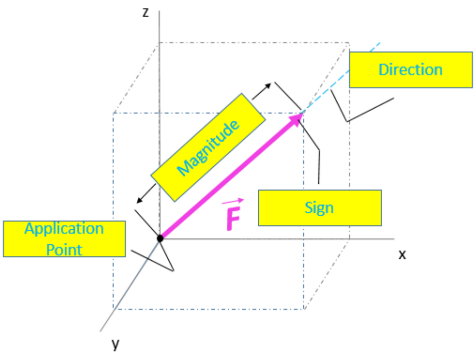

Image 2. Representation of the force vector

Therefore, force, in its most elementary sense, is any agent that can modify the movement or the form of materials; however, when examining forces more carefully, Isaac Newton realised that a force is not something isolated, but part of a mutual action, an interaction, between two bodies. This observation led him to formulate what we know today as the "law of action and reaction" or "Newton's third law".

The law states: "*When an object exerts a force on another object, the second object exerts on the first one an equal force in the opposite direction*". That is, forces interact in pairs and simultaneously. If we push a wall, the wall pushes us with equal force.

PRESSURE

Pressure is the physical scalar quantity that measures the force applied to the surface of an object per unit area. If a force is distributed over a very large surface, then the pressure may be relatively small; by contrast, if the same force acts on a small area, the pressure will be very higher. Pressure is therefore proportional to the force applied and inversely proportional to the application surface. Thus, pressure is expressed in the following formula:

$$Pressure = Force/Area$$

In the SI, pressure is measured in a derivative unit called **Pascal** (Pa), which is equivalent to a total force of a newton acting uniformly in a square meter (1N/m²).

MOMENT

When a body is not supported, the action of a single force will only move it linearly. In order to rotate it, it is necessary to apply two equal forces F and F' in opposite directions separated by a distance D.

The moment of a force with respect to a point shows to what extent there is a tendency in a force or imbalance of forces that can cause a body to rotate with respect to it.

The moment M of a force F with respect to a point A is the **cross product of vector AP (distance) and the force vector F**. The unit in the SI is the N*m (Newton per metre).

M = Distance x Force

Human beings often apply forces through rotation, which generates torques. This moment is caused by a Force (F) acting at a distance from the centre of rotation of a segment. This mechanical system is called a lever arm. There are three types of lever arms depending on the point of support (A), the point of application of the force exerted (E), and the point at which resistance is overcome (R).

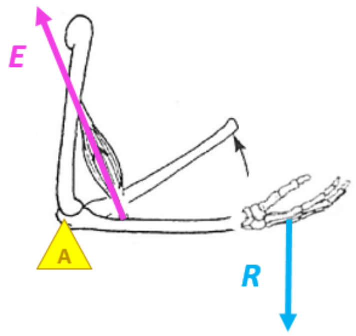

Image 3. Example of third-class lever in the elbow joint (image modified from the Sports Council. ICd series, number 21, 1999)[14]

CENTRE OF MASS, CENTRE OF GRAVITY AND CENTRE OF PRESSURE

The centre of gravity (CoG) of a body is the point of application of the resultant of all the forces of gravity acting upon the different material masses of a body.

The centre of mass of a system is the geometrical point that dynamically behaves as if it were subjected to the resultant forces external to the system. Analogously, it is usually abbreviated as CoM. In physics, the centre of gravity and the centre of mass usually coincide. In these cases, the terms are often used interchangeably, although they describe different concepts.

The location of the CoG in the human body depends on the position that the person adopts. In the standing position with the arms relaxed along the body, the CoG lies approximately anterior to the second sacral vertebra.

The centre of pressure (CoP) is defined as the vertical projection of the centre of gravity. The study of the centre of pressures allows us to quantify the postural oscillations from the reaction forces occurred at the level of the feet as a consequence of the pressure exerted by a subject placed on a system for recording forces such as a dynamometric platform.[15]

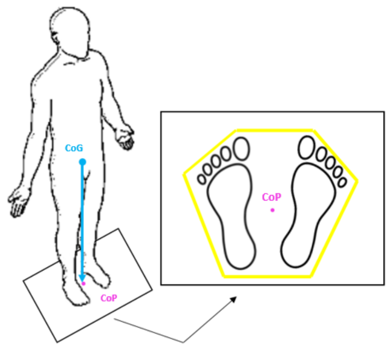

Image 4. Example of visualisation of the centre of gravity (CoG) of the human body in the standing position and the centre of pressures (CoP) on the plane of the floor inside the support base.

Main techniques to assess muscle strength

From the definition of force as a starting point to perform a movement, instrumental techniques, such as conventional dynamometers or isokinetic equipment, are used to record and quantify the response of a muscle or group of muscles to an external request or demand.

DYNAMOMETER

A dynamometer is a static instrument used to measure forces or to weigh objects. The operation of the traditional dynamometer is based on Hooke's law of elasticity, which states that "the deformation of an elastic material is directly proportional to the force applied".

Currently, electronic dynamometers are used, which have replaced springs by load cells or gauges; they measure force and deformation, and they are smaller in size.

In the clinical setting, passive dynamometers are normally used, which measure different muscle groups to determine the weakness degree of the muscles in the upper and lower limbs. They measure the force exerted in the dynamometer itself by stopping such effort using external means or when the evaluator acts against the force exerted. An example of the results is the value of the maximum isometric contraction or the fatigue value provided on the basis of the muscular action assessed.

There are also active systems, which either record the force generated by a person or generate force to work on the person. They use external means to control or stop the force produced, such as mechanical, hydraulic or electric brake systems to dissipate force, and can be used in both isometric and isotonic exercises.

Isokinetic dynamometers fall under this category. They assess the muscle force exerted dynamically in a determined range of motion at a constant and programmable speed. They record the absolute value of the maximum muscle strength exerted in each point of the joint range and the torque of the speed at which the tests are performed, which provides results such as the comparison between the concentric and eccentric work of a muscle group, the force exerted at different speeds, etc. Isokinetic dynamometers, in addition to being used to assess muscle strength, are also used as a sophisticated and versatile muscle-strengthening tool for the rehabilitation of joint injuries, especially in sports.

Main techniques to assess impacts and reaction forces

Instrumental techniques like dynamometric platforms and accelerometry allow us to assess the forces exerted by the human body in contact with the ground during common movements like walking and running with regard to reaction forces and impacts.

DYNAMOMETRIC PLATFORMS

A dynamometric platform is an electronic instrument that allows us to measure and analyse the reaction forces that an individual exerts on the ground when performing a specific movement or gesture. The platform consists of a rigid, flat and static surface placed at ground level, with different sizes depending on the movement to be analysed.

The sensors or transducers are placed below the platform, distributed in a way that they can record the forces exerted on the upper rigid surface. Generally, the platforms currently used have four transducers called load cells, located in the four corners of the platform, and transform a physical quantity (force) into electronic signals.

Finally, the software system analyses the signals coming from the sensors and allows the user to analyse the results.

The most common parameters provided by these recording and analysis systems are the reaction forces in the three directions of space (Fx, Fy and Fz) during the movement analysed, the reaction moments from which the forces and moments are transmitted from the ground to any part of the body, and the centre of pressures as the movement progresses.

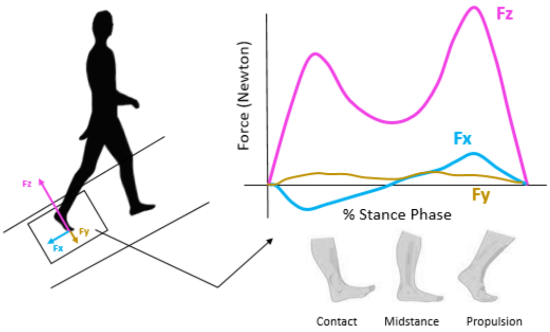

Image 5. Example of the recording of reaction forces in the three axes using a dynamometric platform during foot support in normal gait.

ACCELEROMETRY

Acceleration is commonly measured to analyse impacts and vibrations due to the adequate performance of the equipment available for this purpose. The sensors translate acceleration into an electrical signal, based on the inertia of a mass located on a force sensor. They make it possible to record acceleration in short periods of time and in all three axes of space, depending on the accuracy of the measurement of the acceleration range that can be measured. This provides information about vibrations, shocks and impacts on the instrumented segments.

When assessing a person, joint impacts and shock absorption are usually analysed. Joints act as shock absorbers between the body segments by absorbing the impacts that occur when walking or running. The study of the accelerations that occur in specific body segments allows us to analyse, for example, the characteristics of certain surfaces or the effects of technique on running.

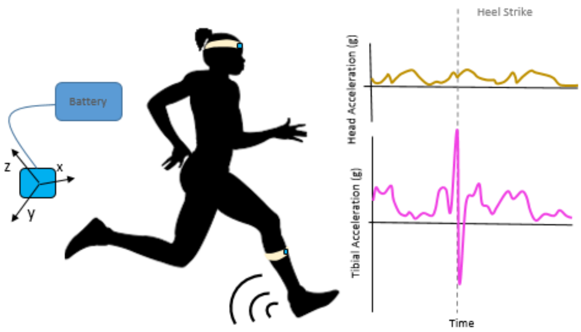

Image 6. Example of the recording of accelerations and vertical forces using accelerometers placed in the tibia and head when running.

Main techniques to assess pressure

These techniques are necessary when recording the reaction forces is insufficient to assess the forces exerted in a body surface when it contacts an object or surface. For that purpose, instrumental techniques such as insoles and pressure platforms are usually used.

Biomechanical assessment in the clinical setting normally uses pressure platforms and instrumented insoles to objectively determine plantar pressures and their exact location on the foot sole during the stance phase of gait cycle. They assess the distribution of pressures on the foot sole both statically and dynamically, the latter being the most frequent because of gait analysis.

PRESSURE PLATFORMS AND INSTRUMENTED INSOLES

The systems to measure pressure have sensors uniformly distributed over their surface, which measure the pressure applied on them and transmit it as an electrical signal to a system that displays the results obtained. There are various types of pressure sensors. This equipment normally uses resistive, capacitive and piezoelectric sensors, with different characteristics regarding repeatability, sensitivity, thermal stability, etc.

Pressure platforms consist of a flat and rigid surface placed at ground level with sensors uniformly distributed in a matrix form, in a way that they can record pressures with equal precision across the measurement surface. These platforms normally use resistive sensors that allow the user to perform measurements either statically, with the subject standing, or dynamically, recording foot support during gait.

Instrumented insoles record the pressures that occur between the foot and the footwear while walking or running, that is, in everyday conditions. These devices can record the support of each foot during the selected gesture. At the same time, the batteries and the wireless transmission of the records make it possible to perform the recordings outside the assessment laboratory.

The study of pressures provides different parameters depending on what is calculated: the centre of body pressures, maximum pressures and average pressures for areas of the foot that were previously established, as well as vertical forces estimation.

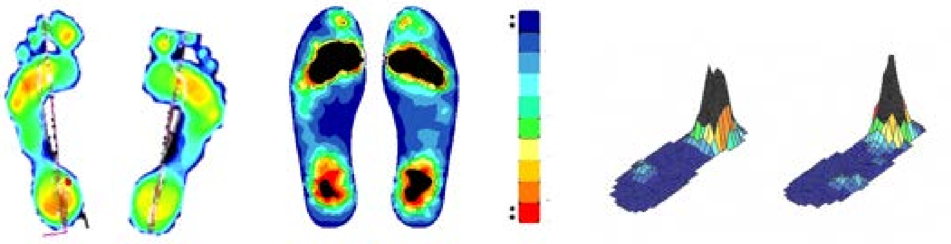

Image 7. Example of graphic information from the analysis of pressures during gait: maximum pressures with bare foot on pressure platform (left) and with instrumented insoles (centre), and isobars representation at a gait instant with instrumented insoles (right).

4.2. Instrumental techniques for the analysis of movement

Concept and classification

The study of human movement involves a detailed description of the changes in the position of the body or some of its parts, as well as identifying the causes that produce those changes. Kinematic studies focus on describing movement without considering the causes that generate it. The instrumental techniques used in the analysis of movements provide information regarding kinematic variables: position, velocity and acceleration.

There are several techniques for the kinematic analysis of movement. These techniques can be divided into two large groups according to the technology they use: those based on the analysis of video images (photogrammetry) and those that use some type of electronic/mechanical sensor (like inertial sensors). This session will introduce the main instrumental techniques of kinematic analysis.

Physical quantities and variables of interest

The main variables related to the study of movement are described below:

POSITION

The position indicates the location of a point in space. This position is represented by a coordinate system and is referenced to an origin. The study of human movement generally uses coordinate systems with 3 axes to define space. In the field of clinical biomechanics, the planes defined by the 3 axes of the space where the joint movements occur are called sagittal, coronal and transverse.

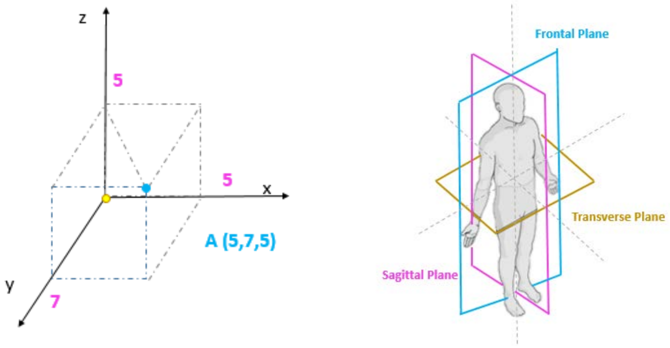

Image 8. Example of coordinates in space (x, y, z) of a point A (left) and planes of movement in human body (right).

VELOCITY AND ACCELERATION

Velocity indicates the change in the position of a point per unit of time. Velocity is a vector quantity and is direction aware. When evaluating the velocity of an object, one must keep track of direction. For example, the gait speed of a subject is the distance travelled when walking per unit of time.

Acceleration indicates the change in speed per unit of time, this variable determines whether the object under study increases speed (positive acceleration) or reduces speed (negative acceleration or deceleration).

In many cases, we intend to characterise more specific movements of the human body such as the movement of the arms or legs. For this type of analysis, we will use the so-called angular variables: angle, angular velocity and angular acceleration.

An angle α is the area of the plane between two half-lines (a and b) that have the same point of origin or vertex (O). In biomechanics, joint angles are usually measured.

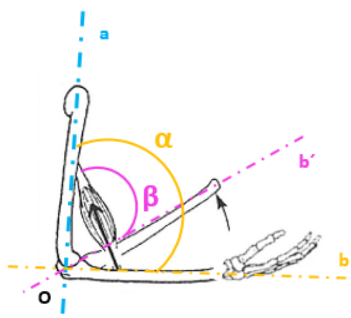

Image 9. Example of joint angle: angle α (a,b) and angle β (a,b´)

ANGULAR VELOCITY AND ANGULAR ACCELERATION

Angular velocity measures the rotation speed of a solid, that is, the angle rotated per unit of time.

Angular acceleration is defined as the change experienced by the angular velocity per unit of time. It indicates if the segment under study increases or decreases its rotation speed during movement.

BIOMECHANICAL MODEL

In biomechanics, the velocity or acceleration of the different segments of the human body are frequently measured. A segment is each arbitrary division of the human body to facilitate its study. The following table shows the main segments.

Segments	Sub-segments
Head	Head, neck
Trunk	Thorax, abdomen and pelvis
Upper limb	Arm, forearm and hand
Lower limb	Thigh, leg and foot

Table 4. Main segments and sub-segments of the human body

The different body parts to be studied are simplified into segments and make up the so-called **biomechanical model**. These models allow us to predict the behaviour, resistance, fatigue and other aspects of the different parts of the body when they are subjected to specific conditions.

Some models can study the kinematics of the human body movement in two dimensions (movement contained in a plane), whereas others study it in three dimensions (the whole space). Depending on the variables that we need to study and the depth of the study, it will be appropriate to use one model or another; however, a thorough study of movement requires a 3-dimension model.

Main techniques to assess movement

GONIOMETERS AND INCLINOMETRES

The manual goniometers normally used in the clinical setting are systems for recording joint angles. They consist of a graduated circle/semicircle with a rotating dial on an axis of symmetry that measures the angle between its arms. Electrogoniometers are used to perform a continuous recording of an angle over time. There are different types of electrogoniometers: those based on a variable resistance or potentiometer that transforms rotation into an electrical signal, which directly provides an electrical signal related to the rotated angle, and those based on strain gauges, which can record the angle in different axes.

Inclinometers are sensors that record the relative inclination with respect to the vertical (defined by the direction of gravity) or with respect to an established reference position. These sensors are accelerometers, which use the inertia of a mass located on a force sensor to measure gravitational acceleration (g). Depending on the inclination of the sensor, there will be a change in the acceleration recorded by such sensor recording a value in degrees. Thus, these sensors perform appropriate measurements with respect to the vertical, but not in the transverse plane, where there is no variation in gravitational acceleration. They are used primarily to assess the range of joint movement, recording the deviation with respect

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to the anatomical neutral posture of the different lower and/or upper limb segments, as well as the cervical, lumbar and/or dorsal spine.

Both devices provide results of the relative joint angles between the instrumented segments. Inclinometers provide the angle measured by each sensor, but they do not identify the plane in which the deviation with respect to the vertical occurs; they cannot be used in fast movements since they are too sensitive to acceleration.

PHOTOGRAMMETRY SYSTEMS

Photogrammetry is a technique for measuring kinematic variables based on images from photographic or video cameras. Photogrammetry equipment mainly consist of a system of cameras and special spotlights, an image recording and processing system, a reference system to calibrate the equipment, and markers to place on the anatomical references or body segments to be assessed, according to the biomechanical model previously defined.

Photogrammetry allows us to obtain information about the position in space of the different anatomical points of the human body from 2D images recorded with cameras. Representing the position of a point in 3 dimensions involves a minimum of two cameras. However, in practice it is recommended that each marker be displayed in at least three cameras. For example, the analysis of human gait requires a minimum of six equidistant cameras arranged in a ring to visualise the whole measurement space.

To obtain the 3-dimensional positions of the markers, it is necessary to calibrate the space of measurement. A reference system is the most common method. This makes it possible to calculate the adjustment parameters of the system, which are the equations that relate the plane coordinates to the spatial ones, both from the spatial (real) data and from the two-dimensional data of the cameras (digitised). The recording speed, images per second, adapts to the performance speed of the gesture. In the example of human gait, the frequency recommended by the literature is 100 images per second.

All the kinematic variables can be obtained from the positions of the points in 3D: angles and their derivatives, which are velocities and accelerations. Nowadays, photogrammetry is still the gold standard technique for the analysis of human movements.

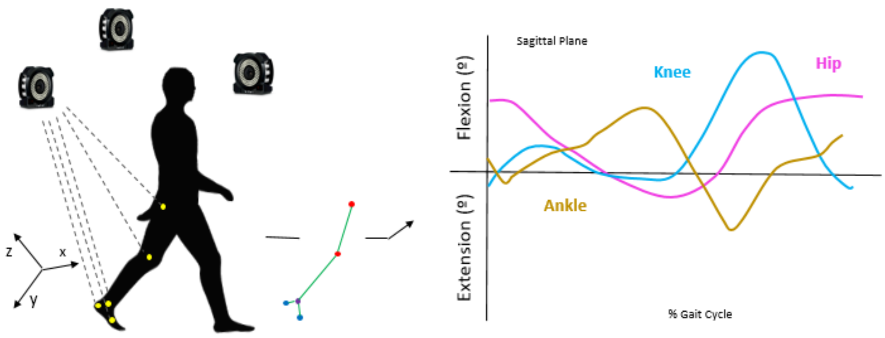

Image 10. Example of the representation of the joint angles of the hip, knee and ankle during the normal gait cycle in the sagittal plane on the basis of the information obtained from a biomechanical model of markers using a 3D photogrammetry system.

However, this 3D technology often involves significant economic costs, it needs special space conditions and has portability limitations. The alternative in some settings is the use of two-dimensional (2D) analysis techniques for assessing joint angles.

These systems usually consist of a standard video camera and software to play the videos and perform the analysis of the movements. For these records to have more validity and reproducibility, the software should include a solution to measure a reference system where the results can be referenced, and the measurement procedure must be performed very carefully; the camera, for example, should be correctly positioned with respect to the measurement area and the person assessed. These are all common sources of error.

These systems have limitations such as the ability to capture dynamic and complex multiplanar movements. As a result of these limitations, the literature offers numerous studies on the reliability and validity of these techniques regarding different types of movements. The results about their validity are varied and dependent on the plane and the movement assessed.

INERTIAL SYSTEMS

An inertial system is an electronic device that measures orientation, angular velocity, acceleration and gravitational forces by using sensors such as accelerometers, gyroscopes (device used to measure angular velocity) and sometimes magnetometers (sensors that measure the strength and direction of magnetic fields). The raw data (evolution of accelerations over time, angular velocities, and tilt for each axis) can be processed using mathematical calculations to obtain, for example, orientation, angles and velocities. As the variable they directly measure is acceleration, the calculation algorithms are still being perfected to reduce possible errors when obtaining absolute positions and displacements.

These sensors are commonly used to extract kinematic information such as joint angles from different segments of the body; they are placed on the body surfaces defined in our study model. Sometimes, complete instrumented suits with these sensors distributed all over the body are used to study, for example, human gait.

They can perform measurements in any environment and reconstruct the trajectories and positions of each body segment in real time in a similar way to a photogrammetry system, which makes it possible to obtain graphs of kinematic variables and virtual animation of the movement, as well as to calculate characteristic parameters.

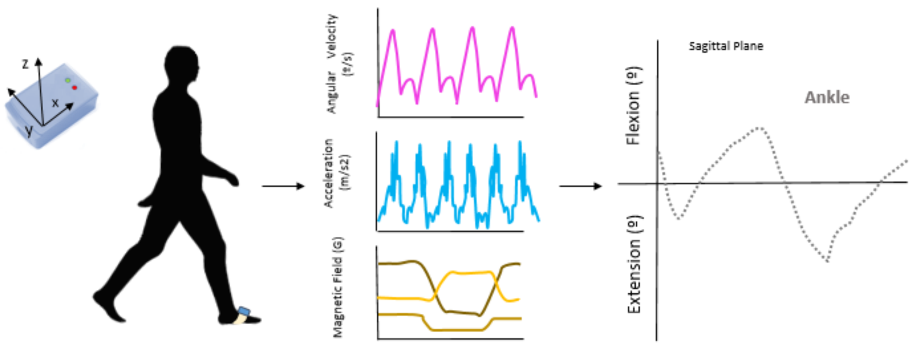

Image 11. Example of representation of the ankle angle during normal gait cycle in the sagittal plane from the parameters extracted using an inertial sensor.

4.3. Instrumental techniques for physiological analysis

The purpose of the physiological analysis is to study the functions of human beings in relation to the environment that surrounds them and the causes that produce changes. These functions are the physical and chemical laws that govern living beings to maintain their internal stability. Instrumental techniques for physiological analysis can explain how certain changes in human functions occur as a result of the adaptation to specific test conditions such as the performance of an exercise, application of a protocol, a large change in temperature, a stressful situation, etc.

This session will refer to surface electromyography because it is the physiological analysis technique most frequently used for biomechanical assessment in the clinical setting. There are more techniques for physiological analysis related to the clinical field such as metabolic system assessment, electrocardiography, surface thermography, etc.

SURFACE ELECTROMYOGRAPHY

Electromyography (EMG) is used as an indirect indicator of muscle activity, that is, it allows us to assess the activity performed by a specific muscle group. It reflects the activation of the motor units, recording and studying the action potential that originates in nerve fibres and muscle fibre.
Surface electromyography (sEMG) captures those signals through electrodes attached to the skin surface. This type of EMG is often referred to as kinesiologic electromyography because it studies muscle function and coordination.

It is important to know the methodology used in sEMG recording, since multiple factors can affect signal acquisition: skin preparation, location and instrumentation of the muscles under study, movement or electrical artifacts, crosstalk (recording signals adjacent to the muscle studied, etc.)

Additionally, the raw signal acquired needs to be processed through filtering, rectification or smoothing. The effective value of the signal is normally calculated (RMS, Root Mean Square) and indicates the level of muscle activation over time during a movement; signal calibration or normalisation is also usually performed to compare the activation levels among subjects or in the same subject due to the variability of the EMG signal. A frequency analysis can be carried out to determine muscle fatigue.

sEMG is mainly used to study the normal function of a muscle during a specific movement and posture by determining which muscles engage in specific movements, in which phase of the movement, and with what intensity. sEMG can answer the questions:[16]

- Is the muscle active?
- Is the muscle more or less active?
- When does the muscle activate?
- Does the muscle become fatigued?
- How much muscle activity is performed? Expressed, for example, as a percentage of the maximum voluntary contraction, also recorded with surface EMG.

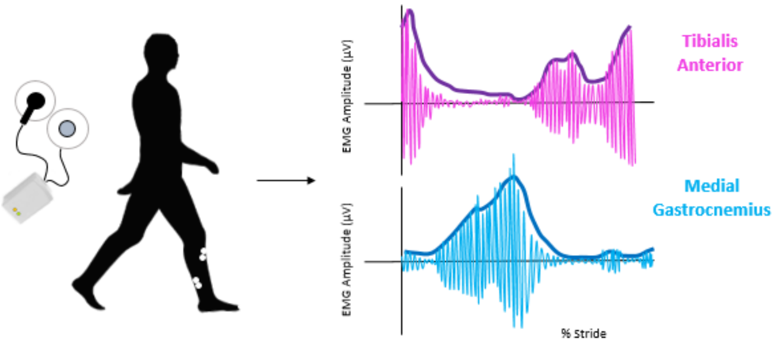

Image 12. Instrumentation example with sEMG of the tibialis anterior and medial gastrocnemius muscle; results displayed through raw signal (fine line) and RMS (thick line) during gait cycle.

4.4 Instrumental techniques for anthropometric and morphological analysis

Anthropometry consists of a series of systematised technical measurements that quantitatively express the dimensions of the human body. Moreover, morphometry is concerned with the variation and changes in the form of organisms, characterised through the anthropometric dimensions and the relationships among them, as well as other type of data such as characteristic points or curves or even the three-dimensional shape of the body or a part of it. Biomechanical assessment is supported by instrumental techniques for anthropometric and morphometric analysis, which deal with the dimensions and volumes of human body and its segments.

The body measurements that can be performed with these techniques include ranges, heights, widths, angles, curvatures, diameters, thicknesses, lengths, perimeters, depths, prominences, etc., as well as information about the three-dimensional shape (geometry) of the segment.

According to the type of measurement and their functionality, measuring instruments can be classified into devices for anthropometric measurement and devices for recording three-dimensional shapes. The most commonly used equipment for biomechanical assessment in the clinical setting is explained below according to the type of measurement performed.

Manual equipment often includes anthropometric tape to obtain perimeters, curvatures and locate the midpoints of the lengths of the body segments, or the stadiometer, to obtain stature.

There is also **equipment based on photogrammetry**, which is used to determine the geometric properties of objects and spatial situations on the basis of an image. For example, plantar print can be studied with the traditional podoscope that uses a transparent surface on which the subject stands and where observation and measurements are made. It can also be studied using a computerised podoscope, which consists of a scanner under a glass plate that accurately captures the footprint. The software associated with this system provides a digital analysis of the print measurements.

Finally, there is **equipment that records the three-dimensional shape** of the body or the selected segments. They are based on three-dimensional digitalisation, which creates a digital geometric model from a physical object (in this case, human body) efficiently and reliably. This model is generated from a cloud of points, usually disordered, that reproduce the geometry of the objects. The options for determining the measurements after scanning and converting the shapes are as important as performing the scan.

At present, several technologies are available to obtain a representation of the three-dimensional shape of real objects. Some require contact with the physical object, but most of them are based on recording the image or signal produced by the transmission or reflection on the physical objects of some type of electromagnetic wave. The appropriate system is selected depending on the technology used, the object of measurement or the segment to be measured. The most common equipment on the market uses active triangulation-based laser technology or structured light projection.

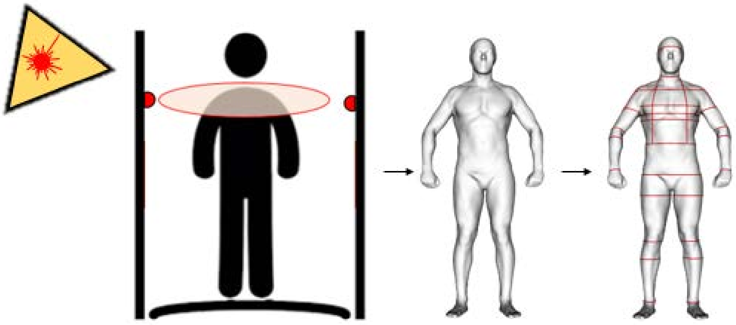

Image 13. Example of laser technology 3D scanner: recording, geometric model and determination of digital measurements.

5. MAIN APPLICATIONS OF BIOMECHANICAL ASSESSMENT IN STROKE REHABILITATION

In the clinical setting, biomechanical assessment makes it possible to measure the clinical changes that occur in a pathological process and to assess the involvement of the functional capacities in a precise and objective way.

Some of the applications of biomechanical assessment in the clinical field that were mentioned at the beginning of the session are applied in rehabilitation. The following examples of application are specifically related to stroke rehabilitation:

- **Gesture characterisation:**

For example, in order to assess the progress of a patient during or after treatment, accurate and reliable information about the gesture or function to be assessed is necessary. The gait functional capacity in the study of people with stroke is determined through specific variables related to biomechanical analysis that characterise the gesture in an objective and valid way. The study by Hall et al.[17] intends to identify those biomechanical variables related to the changes that occur in the self-selected gait speed in hemiparetic subjects after completing a rehabilitation programme. Some of these indicators are described below with respect to:

- Joint kinematics. Plantar flexion of the ankle is directly related to the plantiflexor muscles engaged in propulsion. Hemiparetic subjects who improve their gait speed with rehabilitation, also improve the plantiflexion power of the ankle of the paretic limb.[18,19,20] The hip flexors of the paretic leg can compensate for the weakness of the plantiflexor muscles.[21,22] Thus, an increase in the power of hip flexors in hemiparetic subjects who improve their gait speed is also observed.[18,19,20]

- Reaction forces. The symmetry of antero-posterior reaction forces in the paretic and the non-paretic leg affects velocity. Likewise, the symmetry of propulsion and the propulsive push-off of the paretic leg positively correlate with the hemiparetic severity and gait speed.[23]
- Spatio-temporal parameters. The asymmetry of the step length of the paretic and the non-paretic limb is also related to gait speed.

These variables are recorded by means of 3D analysis systems and an instrumented treadmill for analysing forces. However, new technological approaches to record spatio-temporal parameters in the context of daily life continue to be developed, for example, inertial systems.[24]

- **Selecting the treatment**

Restoration of gait capacity is one of the common goals in stroke patients. The effectiveness of targeted interventions may vary depending on the basal capacities of the patient. Therefore, to ensure an optimal and personalised treatment that obtains the best response from the patient, it is necessary to know the capabilities of such patient. In the gait example, most research, studies and interventions assess this capacity using gait speed as a stratification criterion.[25] Gait speed, called the sixth vital sign[26] is considered a robust tool for predicting gait capacity, rehabilitative potential and quality of life, among others. However, the same gait speed in different subjects can be due to different motor disorders or compensatory strategies that can result in various biomechanical mechanisms. Besides gait speed, an example from the study by Award et al.,[25] we need biomechanical variables that allow us to quantify the patient's capacity in order to apply a specific treatment. The ability to generate a specific propulsive force in the paretic limb would help determine who are the best subjects to undergo a certain type of rehabilitation. This variable is quantified using an instrumented treadmill to analyse force.

- **Treatment efficacy**

In the same way that new approaches and rehabilitation techniques are important, the development of tools to assess the efficacy of such treatments is equally important.[27] One of the objectives of the treatments for rehabilitation of stroke patients is to improve motor behaviour. The analysis of movement through kinematic analysis systems shows differential information regarding motor behaviour. The analysis of the segments or joints allows us to extract parameters such as displacement, velocity and acceleration, and to assess repeatability and particular characteristics like the smoothness of the movement[28] (number of peaks or small adjustment movements at the end of tangential velocity). This is very important in the assessment of motor ability, since these last two parameters are closely related to the patient's coordination ability and consciously selective motor control.[29] These variables, previously monitored during or after treatment, allow us to obtain information about its efficacy in the recovery of motor pattern.

More applications can be established, such as the use of specific variables to set up a treatment, relationships between clinical scales and biomechanical variables, etc. Some of them will be included in subsequent sessions concerned with the assessment and rehabilitation of stroke patients.

6. KEY IDEAS

- Functional assessment is used as an objective tool to obtain information about the capabilities of an individual using biomechanical assessment and its associated techniques.
- Biomechanical assessment involves using instrumental techniques that can be classified according to the object of measurement: forces, movement, physiological and anthropometric/morphological analysis.
- The equipment used by instrumental techniques has different characteristics regarding repeatability, validity, sensitivity to change, etc., which can affect the credibility of the measurement process and the results obtained; consequently, the user of these measurement techniques should know these properties.
- Biomechanical assessment has a wide range of applications in the clinical setting in general, and in the assessment and rehabilitation of stroke patients, in particular.

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