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.2. How can forces be measured and which parameters can be analyzed? What are its main applications?

Index

1. Introduction and objectives

Knowing the force exerted by a body on another or the load exerted on another object is of utmost importance in many biomechanical studies. The techniques used are based on movement analysis, the study of materials, implant development, etc. Just like with other techniques, it is important to know the object to be measured in order to select the most suitable equipment taking into account factors such as the amplitude and frequency range of acquisition, linearity, precision, reliability and sensitivity [1].

For this purpose, a biomechanical analysis normally applies quantitative techniques that use an electromechanical sensor, usually made up of a transducer that converts one form of energy to another. In the case of force analysis, force transducers transform physical quantities of force, pressure, or moments into a quantifiable electrical quantity that can be analysed by a computer; that is, they provide an electrical signal proportional to the force applied to the sensor [2]. There are many types of sensors with their own mechanical characteristics and properties (sensitivity, response time, measurement range, etc.) regarding force measurement such as piezoelectric, piezoresistive, capacitive, strain gauges, etc.

There are two different main fields of force sensors available on the market: those that include load cells, and those that have small force sensing resistor sensors (FSRs).

Load cells can be divided into those based on strain gauges or piezoelectric sensors (Figure 1). In the case of strain gauges, these are stuck to a beam or structural component that bends instantly when a force is applied. Piezoelectric transducers are based on the piezoelectric effect. Monocrystals that produce an electric charge when a mechanical stress is applied are used for this type of sensors [1].

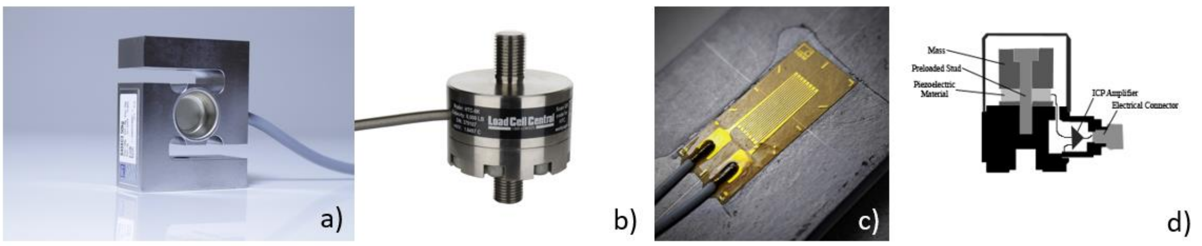

Figure 1 – Imagen of different load cells: a) and b); strain gauge: c), and diagram of a piezoresistive sensor: d).

FSR sensors (Figure 2) are very common devices in biomechanical measurements, especially in those related to the analysis of pressure distribution in the interface between a body segment and an object. These sensors are inexpensive, slim, and the signal conditioning is simple [3].

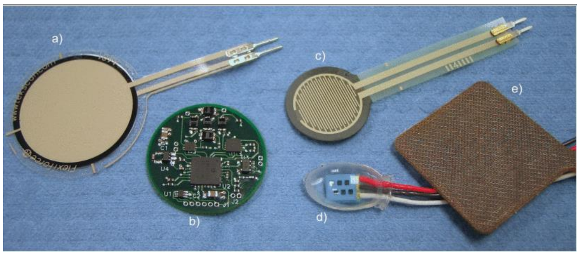

Figure 2 – Image of different force sensing resistor sensors: a) Tekscan Flexiforce A401–25 FSR. b) Sandia Optical 3D force sensor. c) Interlink 402 FSR. d) Sandia Bubble sensor. e) Pressure Profiles C500 capacitive sensor; extracted from Dabling et al. [3].

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

- The major groups of force analysis techniques.
- How these techniques work and the information provided by this equipment.
- The main advantages and disadvantages of using them.
- A brief description of the areas where dynamic instrumental techniques of biomechanical analysis are used.
- Some examples of use and systems based on this type of instrumental techniques.

To facilitate their study, a general classification of these techniques based on the objective of the measurement is proposed below (Figure 3).

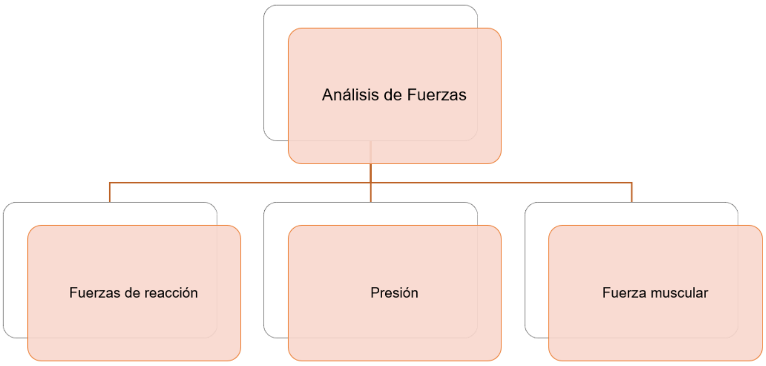

Figure 3 – Example of a general classification of force analysis systems.

2. Reaction forces

Sometimes, the forces exerted by the human body in contact with the ground during common movements such as gait and running needs to be assessed. For this reason, the use of instrumental techniques, such as dynamometric platforms and accelerometry, generates numerical results of the measurement of impacts, damping and the recording of reaction forces.

Dynamometric platforms

A dynamometric platform is an electronic device that allows us to analyse the load that a subject exerts on a flat surface, generally at ground level.

The most common force exerted on the body is the ground reaction force (GRF), which acts on the foot during different movements such a standing, walking or running. This force, of equal magnitude but in the opposite direction to that applied by the individual, is recorded and analysed by the dynamometric platform. Forces are vector quantities, since they cannot be determined only by their value: it is also necessary to know their direction. Therefore, they will be represented and treated as vectors. The reaction force vector is three-dimensional and consists of a vertical component and two shear components that act on the platform surface [2].

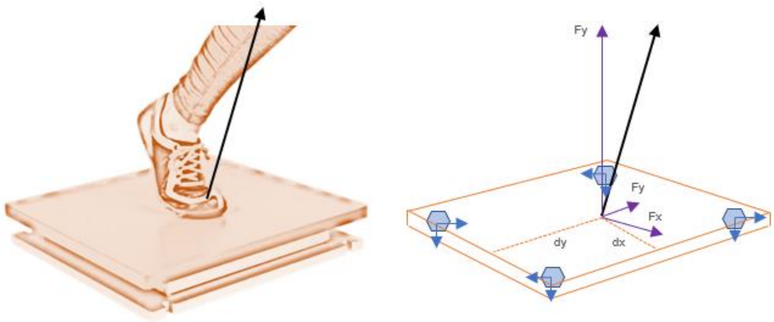

Figure 4 – Representation of the reaction force when stepping on the force platform using four strain gauges; the force is broken down into the three axes of space, as well as the coordinates of the application point.

Dynamometric platforms are usually made up of the following elements:

- A rigid, flat, static surface located at ground level, of varying dimensions depending on the intended use.
- Sensors or transducers located on the bottom of the platform to collect information about the load applied.
- Software to analyse the signal from these sensors and transform it into numerical and graphic results that can be interpreted.

In general, current platforms use four triaxial transducers called load cells, mounted on a strain gauge or piezoresistive sensors, located at each of the four corners of the platform. A calculation process, which uses information from each sensor, provides the three components of the reaction force (Fx, Fy and Fz), the torsional moment on the platform (M) and the coordinates of the centre of pressure (CoP), where it is assumed that the point of application of the load occurs (Figure 4).

During the manufacturing process of this equipment, the sensor coefficient of conversion from volts to force is calculated prior to its use, and then the equipment is calibrated to quantify the measurement error. This process is regularly performed according to the manufacturer as a preventive measure to ensure the validity of the measurements. Given that phenomena such as expansion, contraction or friction affect these sensors because of their mechanical design, an initial tare is usually carried out. This tare involves giving a zero value to the value recorded by the platform before recording the forces of the movement assessed.

Depending on the intended use of these platforms, the most important characteristics that must be considered are:

- Measuring range. The greater the range, the more versatility, since the platform can be used with movements involving great forces (jumps, sports) and small forces (gait, standing); however, increasing the range affects the accuracy of the equipment.
- Overload. It is considered the maximum force that the platform can support, with this being greater than the measurement range.
- Crosstalk. It indicates the force measurement on an axis different from that of the actual application. The lower the cross-sensitivity, the lower the platform error.
- Natural frequency or mechanical resonance. The higher the frequency, the greater the sensitivity to sudden changes in forces, such as those occurred in jumps or rapid sports movements. However, a platform with a high natural frequency may not correctly measure at low frequencies. It is important to ensure that the platform measures constant forces, from a 0 Hz frequency.

This equipment can also be mounted on a treadmill, but the platforms are limited because the type of force plate that can be integrated in the treadmill usually measures only the forces in the vertical direction based on the contact of the feet with the floor [1]. In addition, there are also portable platforms, which can be moved and installed in different environments; however, it can be difficult to study some movements since they are not embedded in a pit to be positioned at ground level.

Currently, dynamometric platform systems are very widely used in different fields such as the clinical setting and sports. Some examples include the *Kistler 3D Force Plate* (https://www.kistler.com/en/product/type-9281e/), a three-dimensional force platform based on quartz piezoelectric transducers; *AMTI Force Platform System* (https://www.amti.biz/optima.aspx), which offers a range of platforms based on strain gauges to measure force in three dimensions; *Dinascan/IBV* (http://analisisbiomecanico.ibv.org/productos/tecnicas-de-registro/dinascan-ibv.html) three-dimensional dynamometric platforms with extensometric force transducers located under the four corners of the platform and oriented two by two in the anteroposterior and mediolateral directions.

Parameters

The usual parameters extracted from the force platforms are the **application point** in 2D coordinates in relation to the measurement plane**,** the **magnitude** in newtons (N) or kilograms (kg) of the **force vector** in the space axes (x,y,z) (Figure 5), and the torsional moment in X (x) generated on the platform.

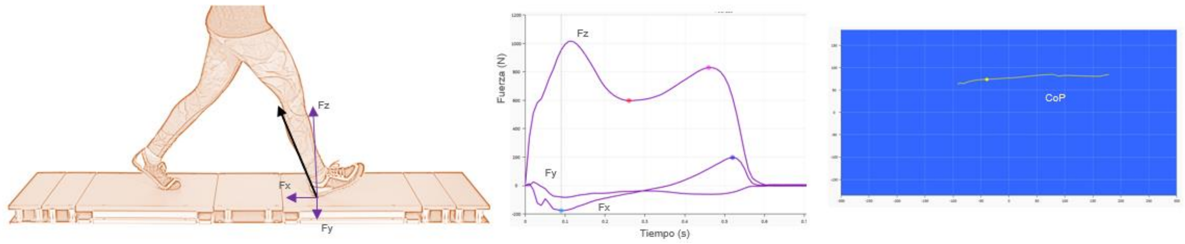

Figure 5 – Visualisation of the three components of the reaction force and representation of the application point (CoP) of the reaction force on the platform during gait.

Advantages and disadvantages

Despite all the features of this equipment, a force platform cannot provide information on how the reaction force is distributed on a surface, such as the foot. For this reason, other force distribution analysis systems have been developed, such as instrumented insoles or pressure platforms, which are described later in this unit.

In some areas, such as the clinical setting, more economical and versatile solutions are used despite their limitations, since this equipment involve high costs and complexity of use.

One of these devices is the WII platform by Nintendo® (Figure 6). This system uses a force platform (Nintendo® WII Balance Board™) which provides information on the displacement of the centre of pressure (CoP) based on the contact of the feet with the platform. Four sensors located in the corners of the platform assess weight distribution estimating the position of the CoP on the x-axis and on the y-axis by recording the vertical reaction force.

Figure 6 - Nintendo® Wii Balance Board™

Although this system offers less features than a traditional dynamometric platform, especially regarding the assessment of quick movements involving great strength, such as jumping and running, it opens a wide range of uses, mainly as a tool for balance rehabilitation, providing information of interest in the study of different populations, training programmes, etc.

In recent years, many works have been published in relation to its clinical applications, such as monitoring the improvement of balance after training programmes in specific populations, and about their validity and reliability in the assessment of postural control. In this regard, various studies evaluate the limitations and functionalities of this system in the clinical setting (Severini et al., 2017 "Use of Nintendo Wii Balance Board for posturographic analysis of Multiple Sclerosis patients with minimal balance impairment"; Weaver et al., 2017 "Use of the Nintendo Wii Balance Board for Studying Standing Static Balance Control: Technical Considerations, Force-Plate Congruency, and the Effect of Battery Life"; Clark et al.,2018 "Reliability and validity of the Wii Balance Board for assessment of standing balance: A systematic review".)

Accelerometers

Accelerometers are sensors that translate acceleration into an electrical signal. In general, their operation is based on the inertia of a mass located in a force sensor, following Newton's second law (F = m x a) to obtain acceleration.

The study of the acceleration that occurs in specific segments allows us to quantify the transmission (impact, damping, etc.) of the reaction forces in specific body segments, as well as to study functions such as gait and balance, and/or analyse and identify specific activities or movements and their level of demand. Depending on the activity or the objective of the study, the accelerometers are placed in the object or segment to be assessed by attaching them to the object to be measured or at specific points or anatomical regions that are key to the study of that movement or function.

There are three common classes of accelerometers: piezoelectric, piezoresistive and capacitive [4]. They have different characteristics depending on the intended application and the conditions in which they have to work. This measuring equipment is usually composed of a sensor, which measures the acceleration values of the vibrations received by the body to which it is attached and transforms the physical parameter (acceleration) into an electrical signal; a signal conditioner, which filters and amplifies the signal from the accelerometer; and a data analysis system, with an acquisition card for the data generated during the measurement and the ability to analyse such data.

There are accelerometers that measure acceleration in one direction (monoaxial), two (biaxial), or three directions (triaxial). The selection of these sensors depends on the movement to be assessed, on the axes from which the information is to be extracted. There are also two key parameters when selecting the right sensor: the acceleration and frequency operating ranges.

With regard to acceleration, piezoresistive accelerometers are used in the study of human gait because of their excellent behaviour in the acceleration range useful for biomechanics (0 to 100 m/s2) and because they can measure low frequencies, from 0 to 100 Hz. These accelerometers can be very light in weight (5 g) and provide great accuracy. Their use is also essential for the study of the shock-absorbing effect of footwear, ortheses or any other mechanism, complement or device (Figure 7).

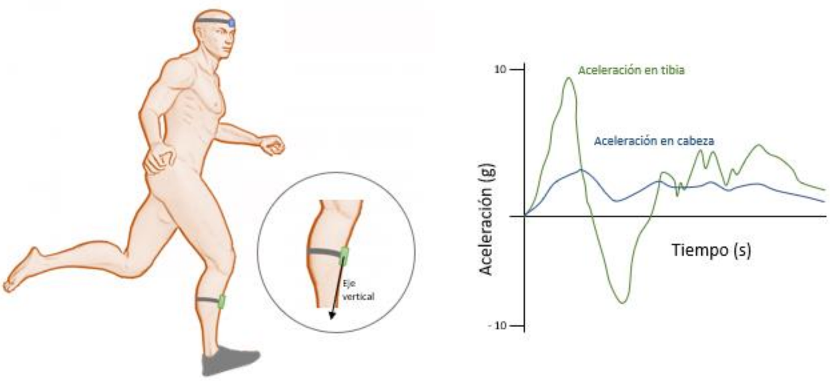

Figure 7 – Assessment of footwear shock-absorption with 2 accelerometers: one located on the forehead (blue) and the other one on the tibia (green). Vertical acceleration peaks are observed in both accelerometers in impact time and run transition.

With regard to the frequency, the accelerations that occur when jumping or running do not exceed 50 gravities (g), therefore, it is not advisable to use wide-range accelerometers, for example 500 g. Moreover, the accuracy of an accelerometer depends on the frequency range to be measured. However, in an accidental impact or hit, 100 or 200 g can be reached. For this reason, accelerometers up to 500 g are used in car-crash tests with dummies.

Currently, these type of sensors can be found associated with others, as in the integration of what is called an IMU (inertial measurement unit), or in a GPS device (global positioning system), providing essential or complementary information to obtain specific variables, or on mobile devices such as a phone or an actigraph.

Parameters

The parameters normally extracted from an accelerometer include an inertial component such as acceleration, although the conversion to forces is easy using the formula F = m x a, with the interpretation or analysis of the results being more intuitive; a static component, such as gravity; and noise, either biological or environmental. The study of acceleration allows us to quantify the frequency and intensity of the movement of the body or object in the three planes of space.

A common parameter when calculating physical activity using an accelerometer are bouts, or periods of activity. Bouts make it possible to know the metabolic equivalent or MET based on the magnitude of the acceleration in the three axes recorded in a specific time interval throughout the recording. This allows us to quantify the type of activity in different categories, from sedentary to vigorous.

By processing the acceleration signal, it is also possible to obtain the time events that characterise a specific movement (Figure 8), such as human gait. In this case, the maximum acceleration peaks occur at heel impact on the ground. Depending on the instrumentation, whether it is applied in one foot or both, or in another segment such as the trunk, parameters such as cadence, step and sway time, double support time, etc., can be extracted.

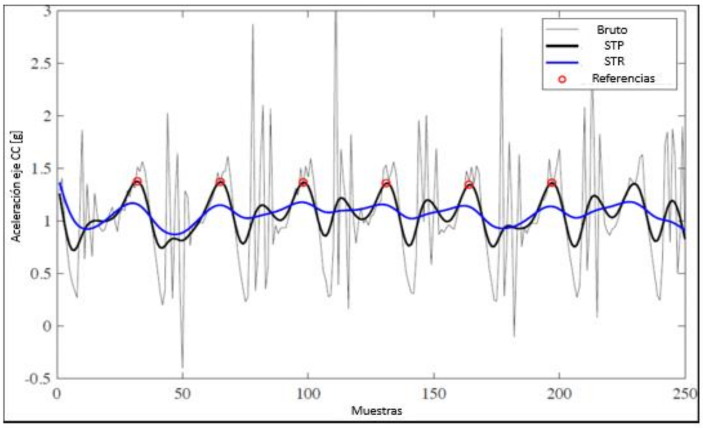

Figure 8 – Example of data from different gait steps obtained by an accelerometer located in the leg: Raw (acceleration in the craniocaudal axis), STP (frequency of step), STR (frequency of stride); extracted from Gurchiek et al. [5].

Advantages and disadvantages

The ability of these sensors to quantify acceleration, together with their low energy consumption and small size, allows us to study movement dynamically; similarly, since they also react to gravitational force, inclinations with respect to the vertical can be statically studied, working as an inclinometer, to analyse body posture, for example.

The inaccuracy of the sensor location, its location in soft tissue, or the associated movement of the interface between the sensor and the segment/object, condition the accuracy and reliability of the measuring system. Besides, if the sensor is located too close to the centre of rotation, the amplitude of the recorded signal may be different [6].

However, the degree of accuracy required depends on what is being measured. For example, determining material damping through the instrumentation of the tibia does not require the same precision as identifying and characterising movements such as walking or rising from a chair.

The reliability and validity of the measurements are subject to signal filtering processes and/or, if there are no sensor calibration or re-calibration processes, a signal offset caused by temperature changes, or general fluctuations in the mechanical gain or wear [7].

As previously discussed, these sensors are part of inertial measurement units (IMUs), along with gyroscopes and accelerometers. This allows us not only to obtain information on the movement, but also to assess the reaction forces that occur during specific activities. For example, there is some equipment available on the market that can evaluate running gait by combining kinematic and temporal variables, as well as those related to impact forces (Figure 9).

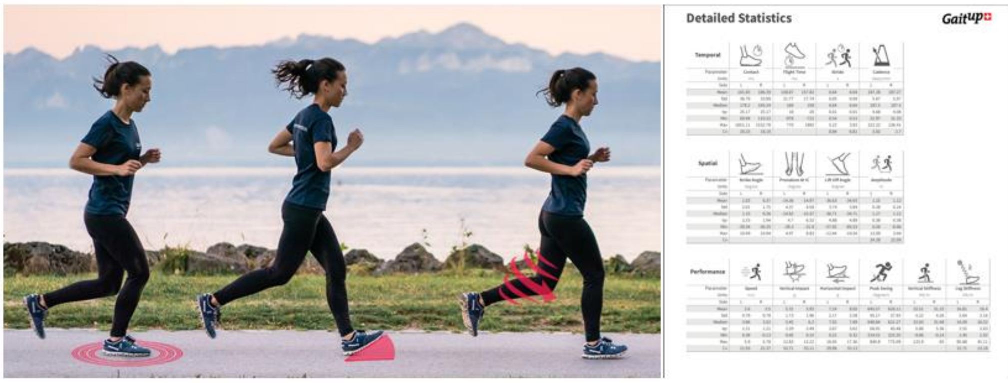

Figure 9 – GaitUp® inertial sensor system for analysing running gait. The sensor is located in the forefoot area of the runner. Extracted from https://gaitup.com/running-analysis/physirun-lab/

3. Pressure

When the recording of reaction forces is insufficient to assess the force distribution of a specific body surface in contact with an object, it is necessary to develop equipment for measuring pressure and provide information on how pressures are distributed around all contact points [2]. The measurement of the interface between body soft tissues and different mechanical devices is very useful for both research and the development of clinical applications. For example, to study pressure distribution on the inner surfaces of the sockets of prostheses, orthoses or corrective insoles in order to assess comfort, correction or risk of complications due to pressure peaks that can potentially cause ulcers or blisters.

The traditional methods used to analyse pressure are mainly **static** systems which cannot determine the shape or load of the surface during operation. They are usually based on moulds that deform upon load or weight, or on image analysis. These traditional systems are mainly intended for the analysis of pressures on the sole of the foot. They include:

- Traditional pedoscope. It is a device used to diagnose, visualise and study footprints and the different axes of the feet. It is used for static footprint acquisition. The traditional model is made up of a transparent calibrated surface, which is the support for the subject being assessed. There are two mirrors under this surface in a fixed position at 45º with respect to the transparent surface. It has a light source directed to the support area on the glass which increases the contrast with the area that is not in contact with the glass.
- Computerized pedoscope. This is a scanner under a glass plate that accurately captures the shape of the foot in 2D while moving in one direction. The software associated with this system provides a digital analysis of the fingerprints measurements obtained.

Recently, dynamic analysis systems based on modern force-sensing resistor sensors have been developed to record pressure distribution during the performance of a body segment.

The basic components of these pressure systems are:
- The **pressure sensor**, which measures and records the physical quantity. It is normally defined as the element that comes into direct contact with the quantity that is going to be assessed. The sensor receives the physical quantity and forwards it to the transducer.
- The **transducer**, which is normally included in the sensor. It transforms the signal sent by the sensor into another type of signal, normally an electric one, both voltage and current, proportional to the pressure recorded by the sensor.
- A data collection system with an acquisition card, and adapted software that calculates and represents the data.
The most common sensors used in this type of systems are capacitive, piezoelectric, resistive and piezoresistive sensors. The characteristics of each of them determine their use depending on the objective of the assessment.

The specifications that must be considered to evaluate the suitability of a pressure sensor regarding the requirements and limitations of their application are **linearity**, which expresses the linear relationship between voltage and current; **hysteresis**, which refers to the difference between output values of the same input, according to the path followed by the sensor; **thermal stability**, understood as the behaviour of the sensor in the face of temperature changes; **accuracy**; **speed of response**; **repeatability**; **size**, and pressure **measurement range**.

The requirements of the pressure sensor for a specific application are low hysteresis, suitable linearity of output and pressure range. A recommended pressure range for gait analysis is approximately 1,00 kPa, but for sports the pressure range should be larger due to the nature of the movements [8].

The equipment shown in this unit will be classified according to the objective: the study of bare foot or in footwear, and in relation to the study of other body segments. Spatial resolution, acquisition frequency, sensitivity, accuracy, and calibration are characteristics determined by the intended use, which influences their design.

Pressure platforms

The objective determination of plantar pressures and their exact location on the sole of the foot during the stance phase of the gait cycle is essential in the diagnostic evaluation and the planning of the treatment of patients with painful disorders or sensitivity in the foot.

Pressure platforms consist of a flat rigid surface on which sensors are evenly distributed in the form of a matrix in such a way that they can record pressures with the same degree of accuracy over the entire measurement surface.

This type of platforms is normally used to analyse the behaviour of the foot during gait. To perform this test, the subject must walk barefoot in a straight line a minimum distance of 9 meters, providing a minimum number of 3 to 5 steps on the platform. This means that data collection requires multiple steps on the platform with no errors.

Instrumented insoles

Instrumented insoles consist of a series of sensors distributed on the surface of a flexible insole located inside the shoe in order to measure pressures in the interface between the foot and the shoe (Figure 10).

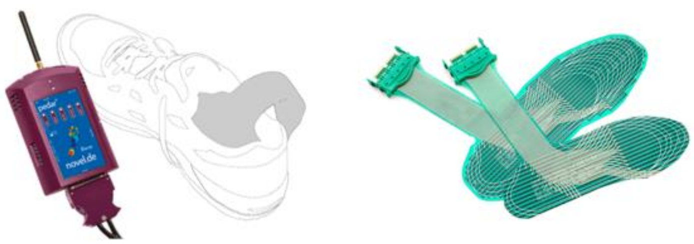

Figure 10 – Examples of plantar pressure analysis systems using a Pedar© instrumented insole by Novel https://www.novel.de/products/pedar/ (left) and the F-Scan System© by Tekscan https://www.tekscan.com/products-solutions/systems/f-scan-system (right).

Insoles provide quantitative and clinically useful data for the functional assessment of gait, plantar pain, prescription and validation of lower limbs ortheses, both in musculoskeletal (either traumatic or not) and in neurological pathologies, or prevention and monitoring of ulcers in neuropathies such as diabetic neuropathy.

This system is made up of sensors embedded in the insoles that collect the quantity and transform it into an electrical signal; a signal amplifier, which conditions the signal to proper levels so that they can be acquired by the acquisition equipment that performs the calculations and shows the results. Due to the nature of the movements assessed, these systems transmit the data via Bluetooth/wi-fi, or integrate memory devices that record, save and allow the data to be downloaded for analysis.

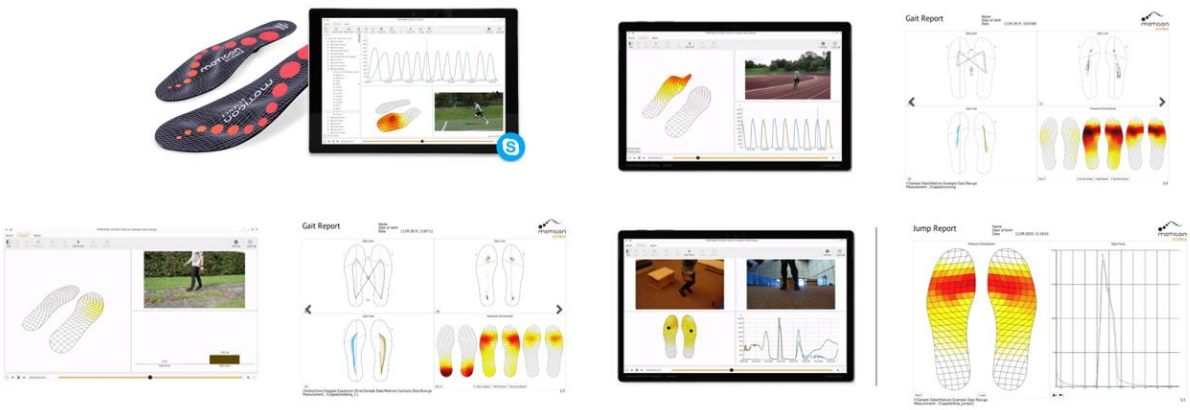

Figure 11- Example of the Moticon Sensor Foot Dynamics® insole system for pressure analysis in different movements and graphic information obtained: gait (bottom left), running (top right) and drop jump (bottom left); extracted from https://www.moticon.de/apps-overview/#outcomes

The instrumentation and portability of these systems make it possible to perform measurements such as human gait and running in different environments and conditions (Figure 11), often outside the laboratory context. This provides relevant information on the behaviour of the materials and footwear design, surfaces, sports technique, orthotic treatments or effects of different interventions in traumatic or neurological pathologies.

Parameters

The usual parameters related to pressure analysis, in this case associated with plantar support, include the representation of pressure curves of each sensor during support time; the maximum pressure recorded by a sensor; the average pressure recorded by a sensor or set of sensors in a specific area, normally associated with an anatomical region such as the heel or the metatarsal area; calculation of the position of the centre of pressure (CoP) and its excursion during the entire support; the calculation of the resulting vertical force, as a result of integrating the information from each sensor in time; etc., as well as relevant information such as cadence, support time or the estimation of angles such as the gait progression angle, etc.

Advantages and disadvantages

It is necessary to consider a series of advantages and disadvantages when selecting a system such as a platform or insoles to perform the measurements. Some of them are listed below:

- Number of sensors, also known as spatial resolution. One of the advantages of using a pressure platform is the large number of matrix-distributed sensors, which provide information on all areas of the foot and facilitate the calculation of the vertical force. The resolution of the insoles is lower than in pressure platforms, but they provide information on the foot-shoe interaction that the platform does not offer and which can be of great clinical relevance, for example, when assessing the correct performance of an orthosis.
- The materials of the insoles, such as polymers or elastomers, the possibility of the sensor slipping, and heat and humidity conditions inside the shoe may alter the behaviour of the sensor and affect repeatability.
- In order to obtain reliable results, it is necessary to collect a minimum number of footsteps to perform the calculations. A problem associated with platform measurements is the “targeting” of the platform by the patient assessed, which means that the patient alters the walking pattern to place their foot in contact with the platform and, consequently, the results obtained are also altered.
- Insoles make it possible to measure gait, and many other movements, outside of a controlled environment, which allows us to assess subjects with alterations such as neurological pathologies that prevent natural movement and support on the platform.
- One of the main limitations of both devices and a source for innovation in this technology is obtaining reliable measurements of tangential pressures due to torsional or shear movements. This type of pressure is exerted tangentially to the surface and therefore the direction of its application is parallel to the surface.

Since both measuring methods have advantages and disadvantages, the selection of the ideal measurement equipment should be based on the characteristics of the movement, the functional capacity of the user and the assistance product to assess [9].

Other systems

In addition to the analysis of foot pressures, there are other pressure analyses related to other parts of the body. For this reason, equipment based on the same pressure sensors has been developed to adapt to the objective of the study.

Pressure mats

Pressure sensors can also be used to determine the pressure exerted by a segment or the entire body on different surfaces. When assessing large surfaces with different profiles or firmness, pressure mats are used. Pressure mats are made of textile-type materials, adaptable to these surfaces, where the pressure sensors are inserted in a matrix.

These mats are used, for example, to assess wheelchair surfaces (Figure 12) in order to evaluate the reduction of harmful pressures sustained over time that can cause ulceration problems. In this regard, they are also widely used to analyse bed surfaces (Figure 12) with bedridden patients, or to determine the pressure distribution of the person on different firmness and mattress designs in search of postural hygiene and comfort.

Figure 12 – Examples of Xsensor© pressure mats to assess the surfaces of wheelchairs and beds, images extracted from https://xsensor.com/applications/wheelchair-seating/ and https://xsensor.com/applications/mattress-design-rd/

Pressure gloves

In this case, sensors embedded in gloves are used to measure the pressure distribution in different areas of the hand in various actions that affect daily life activities, such as grasping, finger pinch (Figure 13), or during the use of some tools or devices, in the field of work ergonomics (Figure 13).

Figure 13 – Example of a pressure analysis system in the Tactile Glove - Hand Pressure Measurement by PPS©, images extracted from https://pressureprofile.com/body-pressure-mapping/tactile-glove

In the sports environment, many sports use devices or tools such as rackets, poles, oars, golf clubs, etc., or the hands as an element for shooting, hitting or stopping the ball, as in volleyball, handball, etc.

This equipment can evaluate the pressure of the impacts, the pressure in each anatomical region and the evolution of palmar or digital pressure over time. This type of analysis assesses functionality during activities involving pressure in the upper limb and studies the influence of the vibrations caused by the sports equipment [10].

4. Muscle force

When it is necessary to quantify the response of a muscle or a group of muscles to an external request, instrumental techniques are used to record the force they exert, such as **conventional dynamometers** and **isokinetic** equipment, or other systems that quantify the force exerted during a specific movement.

Dynamometers

A dynamometer is a static device used to measure forces or to weigh objects. The traditional dynamometer, invented by Isaac Newton, bases its operation on the elongation of a spring which follows Hooke's law of elasticity, which states that "the deformation of an elastic material is directly proportional to the force applied". Thus, knowing the spring deformation constant and the displacement, and applying this law, the applied force can be known [11]. However, this type of dynamometer does not allow us to know the evolution of force over time.

There are various types of dynamometers: hydraulic, pneumatic, mechanical, etc., which have become common in the clinical or sports setting. This is the case of hand strength assessment, where the use of this type of dynamometer is very widespread (Figure 14), due to its portability, easy use, and low cost, although its resolution and accuracy are not adequate in some cases and studies.

Figure 14 – Examples of dynamometers (left to right): mechanical spring (Saehan Smedley Hand Dynamometer), pneumatic (Saehan hand grip dynamometer), hydraulic, (Baseline® Hydraulic Hand Dynamometers) and digital hydraulic (Jamar Plus+ Digital Hand Dynamometer).

The designs have been varied and improved depending on the requirements and the segments or muscle groups intended to be measured. Currently, electronic dynamometers are used, which have replaced springs with elements such as load cells or gauges. They also perform force and deformation measurements, both absolute and over time, not only in a static or isometric position, but also in movement or in an isotonic way, analysing both concentric and eccentric muscular performance.

The objective of this didactic unit is to show some of these dynamometers classified according to whether they are static or dynamic.

Conventional dynamometers

These dynamometers can be defined as static equipment, since they can only measure forces or other quantities such as pressure or moments without movement. They provide a measurement with the body segment to be assessed in a fixed position by recording the result of an isometric contraction of the requested muscle group(s).

Hand-held dynamometers

These dynamometers are not fixed and need the participation of the examiner. In manual dynamometry, the examiner takes the device with his hand and applies it directly to the joint segment to be assessed in order to resist the force exerted by such muscle group in the appropriate direction. The bibliography describes different protocols for this type of muscle assessment, both for the upper and lower limbs (Figure 15), which, in general, seek positions that neutralise the effect of gravity.

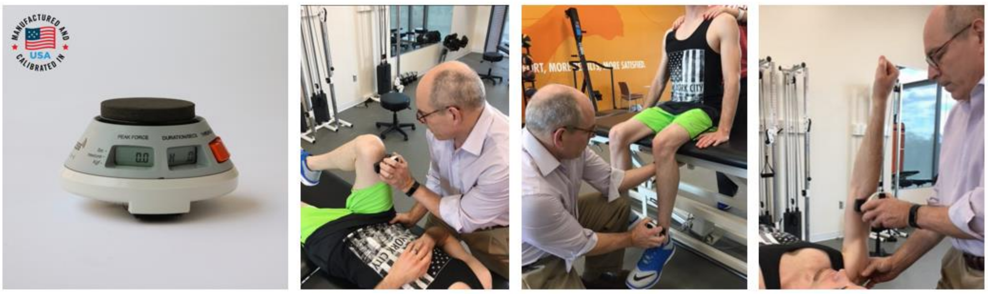

Figure 15 – Example of a manual digital dynamometer: microFET®2 by Hoggan Scientific©, images extracted from https://hogganscientific.com/product/microfet2-muscle-tester-digital-handheld-dynamometer/

Once the dynamometer is properly located, the patients exert a progressive force against the device for a few seconds until they reach their maximum muscular capacity, while the examiner resists this force without moving, and without exerting a force greater than that produced by the subject in order to obtain an isometric contraction, that is, without joint displacement.

The validity and reliability of these measurements depend, in most cases, on the reproducibility of the measurement protocol and on the ability of the examiner to correctly resist the force exerted by the subject being assessed. To improve this aspect, systems to stabilise the segments to be evaluated are also used. Despite this, the bibliography includes studies that describe the results obtained with the manual device correlate significantly with those obtained with an isokinetic dynamometer and with the performance of various functional activities such as sit-to-stand (STS), walking, and climbing stairs [12].

Hand grip dynamometers

The main difference between these dynamometers and the previous ones is their design and purpose, which is exclusively the assessment of the grip strength of the hand, and in some cases, pinch strength.

These instruments can be used by the subject without the help from the examiner. In some cases, their design allows them to adapt to different hand anthropometries and/or assess different grip positions. However, like hand-held dynamometers, in order to ensure the reliability of the results, strict positioning protocols and the instructions provided by the examiner must be followed.
Most of them measure the maximum grip force values, where there is only one degree of freedom and there is lack of versatility in assessing different activities related to hand function. However, the assessment of maximum grip strength is a parameter widely used today, not only to determine the muscular capacity of the hand, but because it is related in many studies with different clinical, psychological and physiological abilities, especially in the elderly. Thus, it can be easily used as an indicator in studies or processes related to aging, injury monitoring, rehabilitation or therapeutic processes in different areas.

Some of them, based on strain gauges and including signal processing software, graphically show force variations over time, which allows us to assess, for example, strength and muscle fatigue slopes (Figure 16).

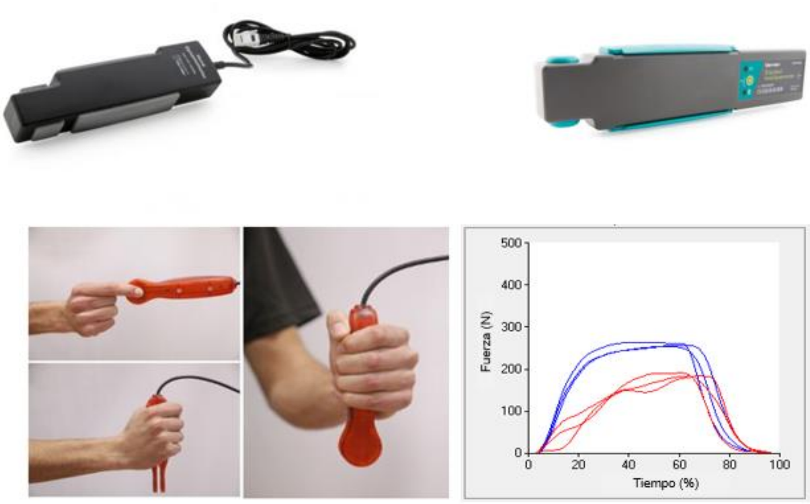

Figure 16 – Example of electronic dynamometers based on strain gauges to measure grip and pinch strength as well as muscle fatigue: (top) wired and wireless dynamometers by Vernier©, images extracted from https://www.vernier.com/products/sensors/hand-dynamometers/, (bottom) example of the NedVEP/IBV dynamometer associated with the NedMano/IBV software, which provides representations of the repetitions of maximum grip strength of the right hand (red) and left hand (blue).

Isokinetic dynamometers

They are dynamic devices since they measure forces or other quantities such as turning moments, with the body in motion and generating displacement. This equipment provides a measurement of such quantities according to time and the type of movement, since the equipment moves with the body to which it is attached or fixed.

These dynamometers resist the muscular force exerted by the subject in the form of a turn (torque) controlling the performance speed at a specific frequency. To maintain a constant performance speed, the resistance generated by the equipment varies depending on the force applied by the subject. For example, when the subject exerts a force that could generate a higher speed than the selected one, the dynamometer increases the resistance so that it acts as a brake and the stable speed is maintained. If the force developed is lower than the force necessary to maintain movement at the set speed, the equipment decreases the resistance to help maintain speed. These instruments provide information on the force applied throughout the range of motion [13].

The first isokinetic dynamometers from the 1960s consisted of a structure containing a hydraulic piston, a controllable valve, a lever arm, and a load cell, which put up passive resistance throughout the entire range of joint movement. Later improvements were made to the so-called active isokinetic dynamometers that included a larger active power source in the form of an electric engine and a computer. In addition, they include a potentiometer mounted on the axis of rotation, which provides information about the angle, and in some cases, a separate tachometer that measures angular velocity [14].

In this way, the capacities of a muscle can be measured in an isometric, concentric and eccentric way under different conditions while obtaining information on the force signal and the moments in real time both in a numerical and a graphic form [15].

Figure 17 – Examples of isokinetic dynamometric equipment (left to right): elbow and knee assessment using System 4 Pro™ by Biodex™, images extracted from https://www.biodex.com/physical-medicine/products/dynamometers/system-4-pro; and cervical spine assessment using MCU Multi-Cervical Unit by BTE™, image extracted from https://www.btetechnologies.com/rehabilitation/mcu/

This equipment is used to assess the joints of both upper and lower limbs and the spine (Figure 17), with the knee being one of the first joints to be studied using this methodology. A common isokinetic test to assess maximum muscle capacity involves performing three or four consecutive contractions after a period of familiarisation with the device and a previous warm-up.

Some factors must be considered when using this measuring technique, such as those related to the subject (age, gender, etc.), the equipment used, and the measurement protocol. The assessment using this type of dynamometer is highly protocolized, since the subject must be properly positioned and the joints to be assessed must be accurately aligned with the rotation axes of the dynamometer to obtain a correct assessment; therefore, the professional who carries out the evaluation should be trained to correctly perform it and interpret the results.

Since they vary the resistance and accommodate the highest overload stimulus throughout the complete range of motion of the joint, these dynamometers are not only used as measuring systems, but also as rehabilitation and training tools for muscle conditioning.

In recent years, the research related to the application of isokinetic dynamometry has focused on methodological issues such as protocol design and reproducibility of the test results, its application in specific groups of subjects and/or patients, and its implementation in the medicolegal field [15].

Parameters

The parameters that are usually extracted from this equipment are those related to strength. The main result provided by conventional dynamometric equipment is the absolute value of the maximum muscle strength, generally expressed in Newtons. From this value it is possible to obtain the **average strength** (average of the maximum muscular strength performed in different repetitions), variability of the measurements using, for example, the **coefficient of variation** (standard deviation of the maximum forces with respect to the average strength expressed as a percentage), or the **index of strength loss** with respect to the assessed muscle group of the contralateral limb.

Isokinetic devices provide information on the absolute value of the maximum muscle force (N) exerted at each point of the joint range, the **torsional moment or torque** (Nm) and the **angular velocity** (m/s) at which the test was performed. The **maximum value of the moment/force** in the curve of the angle position with respect to the moment (MAP) (Figure 18) is considered the standard measurement in isokinetic tests.

Additionally, the results of an isokinetic assessment are usually expressed as a comparison or percentage. The parameters usually calculated are **bilateral comparisons** (difference in strength between the dominant/contralateral limb and/or healthy/pathological limb), **sequential** comparisons (differences between two different periods or situations), comparisons with **type curves** of the torque, comparisons between **opposing muscle groups**, comparisons between the **concentric and eccentric work** and comparisons of the force exerted **at different speeds**.

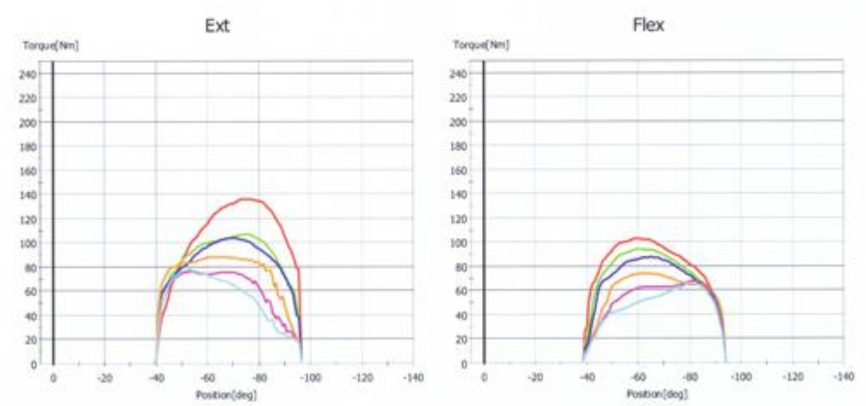

Figure 18 – Example of a representation of the MAP curve of an extension movement (left) and a flexion movement (right), image extracted from https://www.isokinetics.net/index.php

Advantages and disadvantages

The advantages of manual dynamometric systems include portability, low cost, and ease of use compared to isokinetic dynamometric systems.

One of the main disadvantages of using hand-held dynamometers is the influence of the examiner on the reliability of the measurements. For the evaluation of weakened or injured muscle groups, the results, validity and reproducibility are adequate; but this can vary depending on the strength of the examiner, the variability of the placement of the dynamometer perpendicular to the direction of the force and the muscle group assessed; for example, the results obtained for the lower limb are usually less reproducible than those of the upper limb, where the greatest force generated is higher.

Isokinetic systems have a number of advantages over conventional hand-held dynamometric systems such as the safety of the subject during the performance of the movement against an accommodative resistance, strict and well-defined protocols, the ability to accommodate resistance, the selection of the performance speed, and the assessment of muscular strength through concentric and eccentric, as well an isometric work.

Besides, they allow us to objectify the curves of force/range of movement and compare the different values obtained within an examination, as well as with those from other examinations. It is an accurate device for evaluating muscle function as a whole or at different points of the joint range.

However, the interpretation of the force results obtained with isokinetic equipment is not without difficulty; other disadvantages include the influence of the acceleration/deceleration periods, the influence of the variability of the measurements on the calculation of certain parameters, or the lack of standardized procedures despite intensive research and widespread efforts to optimise the tests.

Some studies also argue that the dynamic force measured by this equipment has little relation to the functional state of the patient after a conservative or surgical procedure.

5. Main areas of application

Instrumental techniques of force analysis make it possible to know how human movement occurs by analysing different variables. Force analysis provides information on why a movement occurs and complements the descriptive analysis of the movement provided by kinematic information. The study variables are determined in the measurement procedures selected to characterise the objective of the study.

These instrumented biomechanical analysis methodologies are implemented in some areas on a day-to-day basis due to the improvements of these technologies in terms of portability, incorporation to textile materials and connectivity with mobile apps, as in the case of pressure analysis systems. However, it is important to correctly specify the technical characteristics of the equipment, procedures for use, reliability and validity in relation to the applications for which they are intended in order to avoid inappropriate use by professionals, teachers or end users.

The most common areas of use are those related to the clinical setting, sports and ergonomics. Some of the most common application cases in these areas are listed below.

Clinical setting

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

- To characterise normal movements and movements that are characteristic of specific pathologies, both neurological and musculoskeletal, especially in relation to gait.
- 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 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 associated with anatomical variables, techniques and the physical characteristics and behaviours of the materials used in sports practice.

- 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., mostly related to the reaction forces and pressures generated in human gait and in the maintenance of balance, as well as the assessment of the different manifestations of muscular strength.

Rehabilitation

The current increase in life expectancy causes the aging of a higher percentage of the population. This population will demand more healthcare due to the progressive loss of their functional capacities associated with the risk of decreasing their functionality or suffering neuromuscular pathologies. This functional loss, for example, is associated with the risk of falling with important consequences for people's quality of life. This affects health systems, since their healthcare capacity can be significantly reduced.

In this context, solutions are sought through new low-cost technologies that provide alternatives to hospital treatments and allow for remote monitoring and control. The systems that record movements and forces, usually in an environment based on video games, make it possible to implement training and rehabilitation exercises, and to monitor progress. The increasing number of these initiatives in the clinical setting provide evidence of their effectiveness. One of these reasons is the ability to create adherence to the treatments due to the technological and recreational component that these tools provide.

As an example, the use of the Nintendo© Wii Balance Board (WBB) is increasingly widespread within the clinical community because of its multiple advantages such as price, portability and performance, which is comparable to that of higher-cost equipment, especially in rehabilitation. Most proposals for guidelines and rehabilitation training using this platform are intended for patients with neurological (hemiplegia, Parkinson's, Alzheimer's, brain damage, etc.) or vestibular pathologies. The paper by Llorens et al. [16] “Balance rehabilitation using custom-made Wii Balance Board exercises: clinical effectiveness and maintenance of gains in an acquired brain injury population” studies if training with customised rehabilitation exercises using the force platform (Figure 19) improves balance in a sample of subjects with acquired brain damage and whether this effect lasts over time in the absence of this training. One of its conclusions indicates that performing exercises with this equipment provides lasting beneficial effects in the studied sample compared to a control group using conventional treatments.

Figure 19- Patients interacting with the prototype of the easy balance virtual rehabilitation system (eBaViR), images extracted from Llorens et al. [16].

Evaluation of the effect of an intervention

The main objective of surgical procedures after a musculoskeletal injury is to restore the damaged joint to its previous state or with the greatest possible functionality. One of the main variables to evaluate the results of the surgical techniques used is muscle strength. In order to assess the effectiveness of a surgical intervention, the isometric assessment of a specific muscle group does not provide the necessary information and it is necessary to assess strength throughout its complete joint range.

The study by The et al. [17] "Long-term functional results and isokinetic strength evaluation after arthroscopic tenotomy of the long head of biceps tendon" assesses the biomechanical function of the upper arm after an arthroscopic tenotomy of the long head of the biceps (LHB) in long-term follow-up. The instrumental technique used to measure force is the Biodex® system (Biodex Medical Systems, Shirley, NY, USA). The isokinetic force is assessed at a speed of 120º/s throughout the full range of elbow flexion and supination, both in the injured and the healthy arm. The study variables, in this case torque for a subsequent analysis, are average peak torque values and total work (the area under the curve after graphically representing torque values during the joint range) performed throughout the full joint range (Figure 20). One of the conclusions of this study shows a significant reduction in the force peak in both elbow flexion and supination; however, the clinical function remains good due to the fact that the muscular compensations of the upper limb preserve the power and work done throughout the joint range.

The objective of these studies is to evaluate the results of a surgical technique in specific injuries, populations and requirements. This makes it possible to ensure the correct prescription or to propose modifications, which contributes to the advance of treatments.

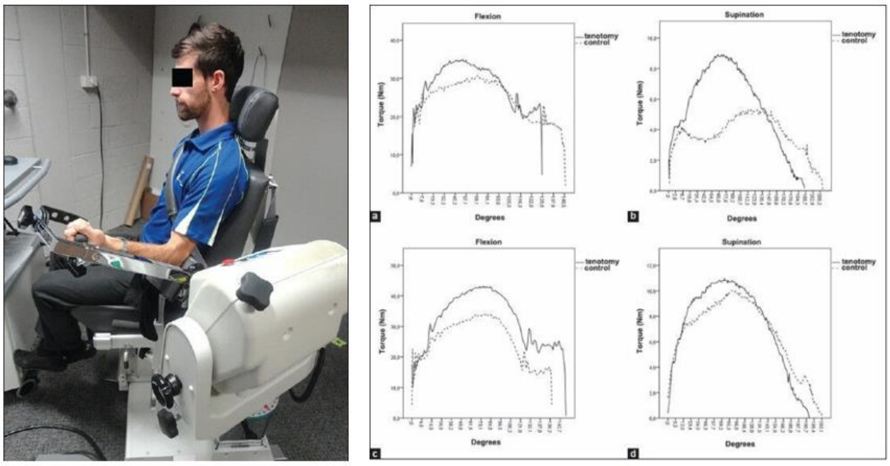

Figure 20 – Positioning of the patient in the Biodex® system (left) and results of the torque curves of the healthy arm (dashed line) and the injured arm (solid line) of two patients for flexion and supination (right), images extracted from The et al. [17].

Activity monitoring

Diabetes causes alterations at the circulatory and peripheral neurological level that affect the sensitivity and proprioceptive capacity of the lower limbs during gait. One of the problems associated with this pathology is the development of foot ulcers, which is one of the main causes of hospitalisation in people with diabetes. If factors such as excessive increases in pressure, temperature and/or humidity are not controlled, serious circulatory problems can occur and result in serious skin conditions, such as ulcers, or even amputations.

Initiatives such as the Orpyx® SI system can record plantar pressures and temperature thanks to a sensorised insole. This recording analyses footprints in daily life and informs users about the evolution of their footprint through a mobile app; in addition, it collects the data and sends them to the medical professional in order to avoid possible complications (Figure 21).

Figure 21 – Orpyx® SI, sensorised insole, mobile app with graphic information, and record of the subject's daily activity, images extracted from https://www.orpyx.com/.

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.

The use of instrumental techniques of biomechanical analysis makes 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 [2]. The main applications of the analysis of reaction forces and pressures focus on the analysis of the running technique, interaction with the footwear or various materials related to shock absorption and coefficients of friction, the ability to control balance, as well as the study of muscle strength and its main manifestations in sports, such as the maximum dynamic force, maximum explosive force, etc.

Risk factors in sports injury prevention

Injuries involve periods of sports inactivity, and in some cases, they even prevent the person from returning to normal practice with a certain level of demand. For this reason, the identification of factors that can increase the risk of injury is one of the main objectives within sports, especially at a professional level. There are many clinical, radiological or physiological tests that study various factors contributing to injuries. In this regard, there are also factors related to the biomechanics of the sports movement that allow us to analyse using these biomechanical analysis techniques specific variables of the sports movement associated with the occurrence of injuries.

Force analysis is one of the methods used to achieve this objective. A couple of examples are included below to illustrate the potential of these force analysis systems in the study and prevention of sports injuries.

Anterior cruciate ligament (ACL) injuries are one of the most important knee problems in sports. An ACL injury and the subsequent rehabilitation takes long periods of time and, in some cases, it prevents the person from returning to high-level and demanding sports practice. It is important to know the mechanisms that cause this type of injury, objectify the factors necessary for the recovery and establish the ideal recovery time. There are multiple internal (anatomical, physiological, etc.) and external (footwear, surface, etc.) factors that influence this injury, some of them related to the biomechanics of the lower limb. One of the most studied aspects is the influence of the biomechanics of the lower limb joints on jump landing actions, like its effect on specific risk factors of injury such as dynamic knee valgus. As an example, the paper by Tran et al. [18] "The effect of foot landing position on biomechanical risk factors associated with anterior cruciate ligament injury" studies the influence of foot position on jump landing (Figure 22). For the recording of reaction forces, Bertec force plates are used (Bertec Corporation, Columbus, OH, USA) synchronised with optical movement analysis equipment to obtain the study variables.

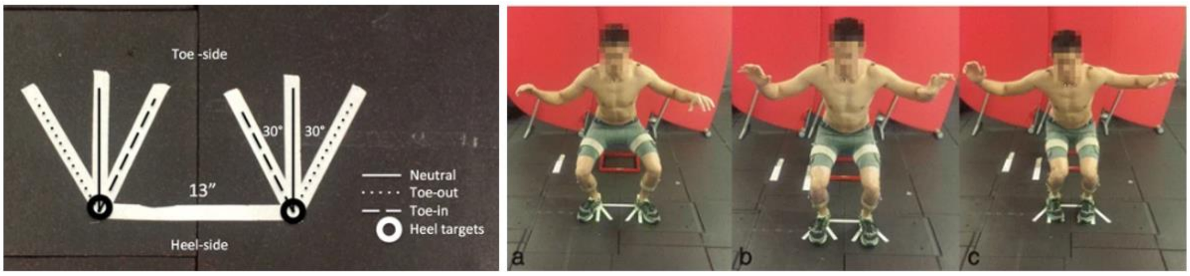

Figure 22 – Template on the platform which shows the three foot positions in the landing (left) and example of jump reception in these three positions: toe-out, neutral, and toe-in; images extracted from Tran et al.[18].

The results of this study show that the toe-in landing position increases the number of risk factors associated with ACL injury. Changing the foot position on the ground appears to significantly alter the biomechanics of the lower limbs in both men and women during a double-leg jump and may be an objective for movement pattern modification [18].

In the case of running, there are various systems for analysing plantar pressure to characterise the athlete's footprint, and as in the following example, to monitor and analyse footprint changes while running, in addition to recording different variables associated with training. The SensoriaFitness® system consists of a sock with pressure sensors in specific areas of the foot, which measure the changes that occur in the support while running and transmit the information in real time to a mobile app (Figure 23). Thus, users can see the information about the changes that may occur in their training and might be related to a possible risk of injury.

Figure 23 – Pressure sensor system embedded in the Sensoria© Smart Sock, Sensoria© Core, and Sensoria® Run app, images extracted from https://www.sensoriafitness.com/

Sports technical assessment

Running is one of the most practiced sports worldwide. An increasing number of people practice running on an amateur level. One of the reasons is the fact that you only need a pair of shoes and time available to practice running. However, as in other disciplines, the sports technique and the material used are important elements for an efficient performance and injury prevention. Many works focus on the study of different variables such as the footstep reaction forces, and more specifically, on the reaction force in the foot strike phase.

For this type of study, dynamometric platforms are used to analyse the vertical reaction force of the foot strike. As an example, Figure 24 shows the different morphologies of the impact force according to the kind of foot strike running barefoot or in footwear. In addition to characterising the type of running technique (forefoot, midfoot and rearfoot), they allow us to study the relationship of the technique, the efficiency and the risk of injury mentioned above.

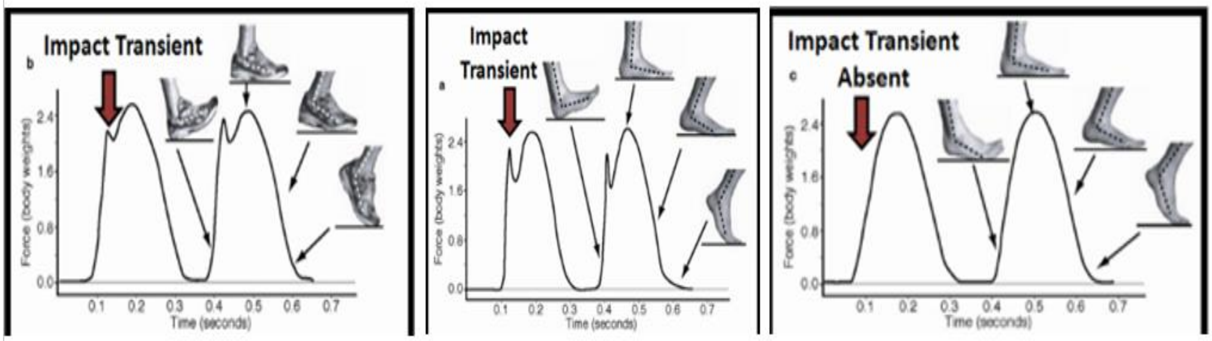

Figure 24 – Morphologies of vertical reaction forces when running with initial rearfoot impact in footwear (left), barefoot (centre), and midfoot support barefoot (right) , images extracted from http://barefootrunning.fas.harvard.edu/4BiomechanicsofFootStrike.html

In the field of **ergonomics**, instrumental techniques are used in the occupational setting to record muscle load and capacity during the performance of different tasks. This makes it possible to research, study and develop methodologies for the correct adaptation of the environments and products, and to determine, for instance, the risk of musculoskeletal disorders. These techniques also allow us to design and validate different products or environments from an ergonomic perspective, that is, considering the needs and characteristics of the subject.

Simulation of jobs and work tasks

There is some equipment that can assess, for example, muscle strength during the performance of specific tasks similar to work tasks. This allows us to know the muscular capacity of specific muscle groups of the individual when performing tasks associated with the requirements of the job and to study their performance. Besides, this can also be used for rehabilitation activities.

An example is the BTE© Simulator II® equipment (Figure 25). This equipment can reproduce multiple activities of the upper limbs related to work or daily life tasks, including the ability to assess muscle strength in an isometric or a concentric isotonic way and generate assessment and rehabilitation protocols.

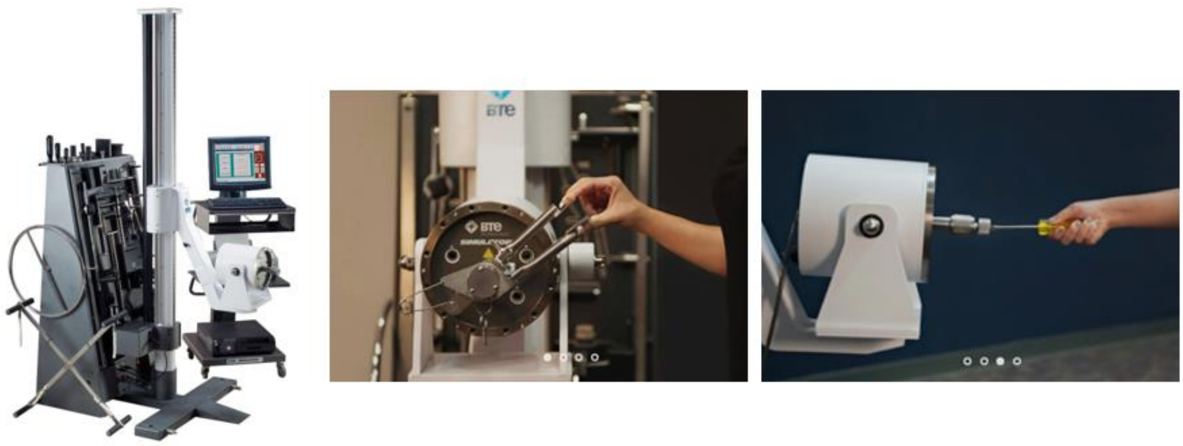

Figure 25 – The BTE© Simulator II® and an example of muscle strength assessment in daily activities (digital pinch) and/or work activities (screwing), images extracted from https://www.btetechnologies.com/rehabilitation/simulator-ii/

Product assessment

These devices can also be used in the design or assessment of products following ergonomic criteria. This evaluation allows us to compare the results obtained with reference criteria.

The recording of pressures to analyse the interaction between the subject and a product provides an example of this. For instance, the Tactilus Bodyfitter® system by Sensor Products Inc. (USA) consists of a pressure mat that analyses the pressure distribution and the magnitude between the subject and the lying surface. This information is recorded and graphically provided through pressure maps (Figure 26).

Figure 26 – Example of an analysis of the pressure distribution between person – mattress using the Tactilus Bodyfitter® system and pressure map (right), images extracted from https://www.sensorprod.com/dynamic/mattress.php

7. Key ideas

The main key ideas of this didactic unit are:

- There are different types of sensors with different characteristics to analyse force in biomechanical studies.
- The main force parameters extracted from these techniques are related to the recording of the reaction forces in the three axes of space, pressures, accelerations and muscle force.
- These sensors are included in different equipment depending on the object to be measured and their characteristics.
- In order to select a sensor according to the object to be measured, it is necessary to know the technical characteristics and specifications of the different sensors, as well as their measurement procedures.
- Specific instrumental techniques of biomechanical analysis are implemented in areas such as the clinical setting, sports and ergonomics with multiple applications.
- The ongoing technological development, such as portable recording systems and connection to mobile apps, will allow new applications for biomechanical assessment to be developed and extend its areas of application.

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