EBOOK: PART I

Intro to Plantar Pressure Mapping in Sport

How plantar pressure measurement systems can help biomechanics professionals minimize athletic injury and maximize human performance in their clients.

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XSENSOR | Intelligent Dynamic Sensing

Intro to Plantar Pressure Mapping in Sport
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Introduction

Foot Pressure Mapping from Past to Present

The technology behind foot pressure mapping, also known as baropodometry or pedobarography, has been used for decades in mainly clinical settings to analyze plantar pressure and gait disorders in pathologic and orthopaedic patients. In research labs, it's used in combination with other technologies like motion capture and surface electromyography to analyze biomechanical variables.

Historically, most of the collected data from foot pressure mapping in clinical settings has been focused on customizing orthotics and managing peak pressures in diabetic patients to mitigate or prevent ulcers.

In research labs, foot pressure mapping has been mainly used as an integration method — many clinicians prefer it over force plate measurements and motion capture systems.

In the past, biomechanics research has taken a reductionist approach by trying to answer the question of how (kinematics) and why (kinetics) motion happens, with little focus on the ways kinematics and kinetics are expressed through the function of the foot.

Origin of the Term 'Foot Pressure Mapping'

Foot pressure mapping is a modern adaptation of an early-twentieth century technology.

Early methods of measuring pressure distribution between the foot and a supporting surface has been historically known as pedobarography or baropodometry.

The etymology of the term derives from the Latin word pedes, standing for "foot", and the Greek word baros, which refers to "pressure".

Today, the term pedobarography generally refers to the early method of measuring plantar pressure using a mat with rubber and ink.

At present, the term foot pressure mapping or plantar pressure mapping is generally used to describe modern electronic systems that use hardware and software to create pressure maps during an entire gait cycle to analyze pressure data.

Kinematics of Loading

When it comes to understanding the advantages of integrating plantar pressure mapping technology in sports, we need to consider how the ankle-foot complex functions and contributes to human locomotion and performance.

Though the subjects of foot anatomy and gait cycle dynamics are not covered in detail in this book, it's important to understand some basic concepts as they relate to plantar pressure mapping technology.

Starting with the talus, this bone plays a crucial role in ankle-foot mechanics and is responsible for the transfer of body weight to the foot through three main joints: the ankle joint (talocrural), the subtalar joint, and the talocalcaneonavicular joint.

During high-impact activities, such as running or jumping, the ankle-joint reaction force can be more than 13 times the total weight of the body. [1]

In this context, the subtalar joint plays a fundamental role in the ability of the foot to properly perform its two mechanical functions during locomotion:

- Acting as a shock absorber and mobile adaptor to adjust to uneven terrain, and
- Being a rigid lever for forward propulsion [2]

These mechanical functions distribute body load carried by the ankle joint during walking, running and jumping.

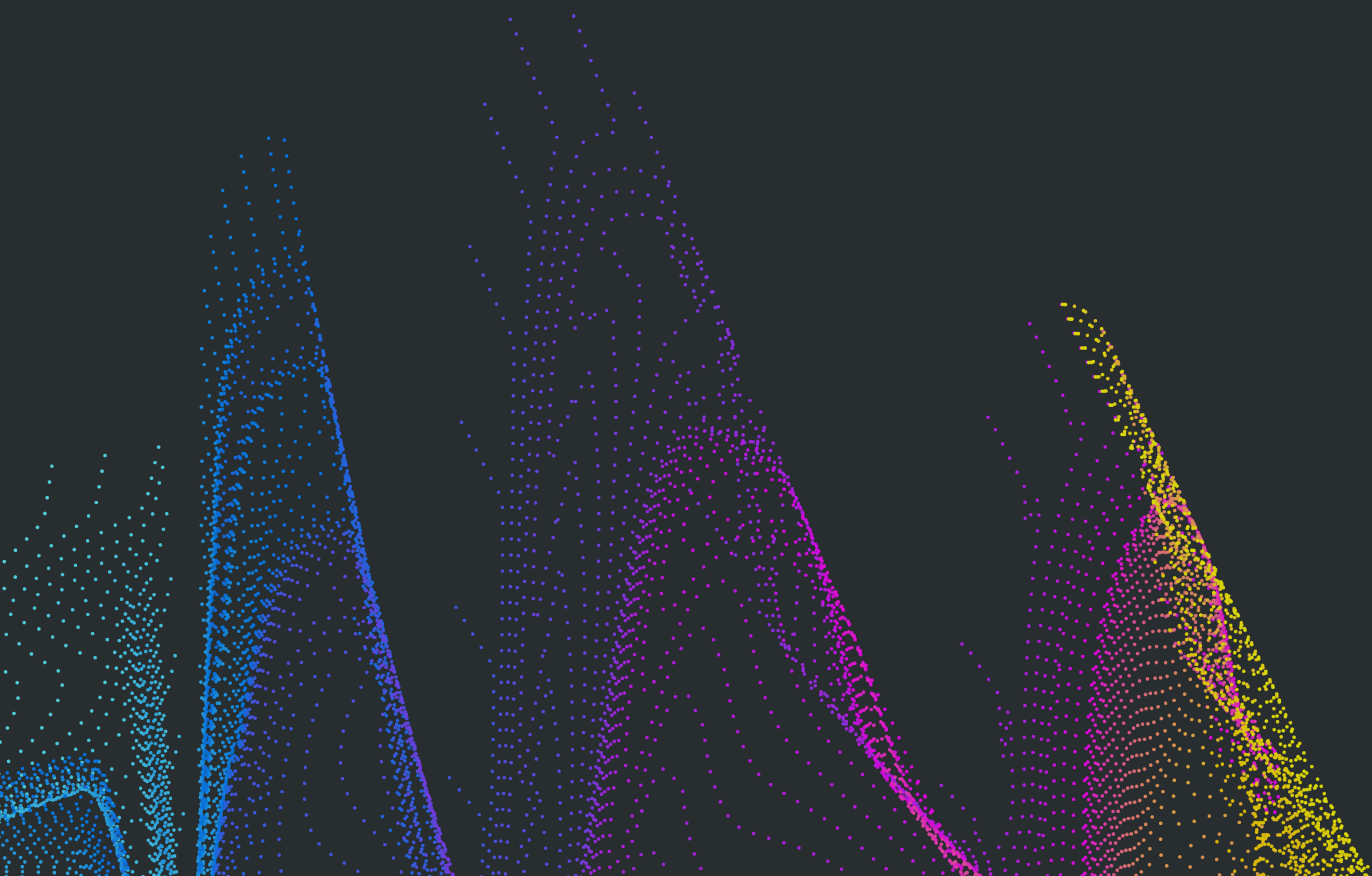
With the above in mind, it's clear that limiting biomechanical assessment to measuring force production can leave a lot of information about human performance on the ground.

By adding pressure measurement, we can now analyze how force is distributed over the entire foot as well as the bilateral timing of loading, which is critical in gaining insights into and improving human performance. We can call this "kinematics of loading" or "geometry of loading": the way the load reaches its goal by using different trajectories over time.

CHAPTER

01.

Introduction to Foot Pressure Mapping Technology



Introduction to Foot Pressure Mapping Technology

The aim of this chapter is to help you understand how plantar pressure mapping technology works and the most relevant technical components of pressure measurement systems.

The technology behind plantar pressure mapping measures the pressure on a specific set of transducers positioned between the sole of the foot and:

- The ground (pressure mat), or
- The shoe (pressure insoles)

First, let's look at what kind of data and metrics are being measured by these systems. There are two sets of data, measured either directly or indirectly:

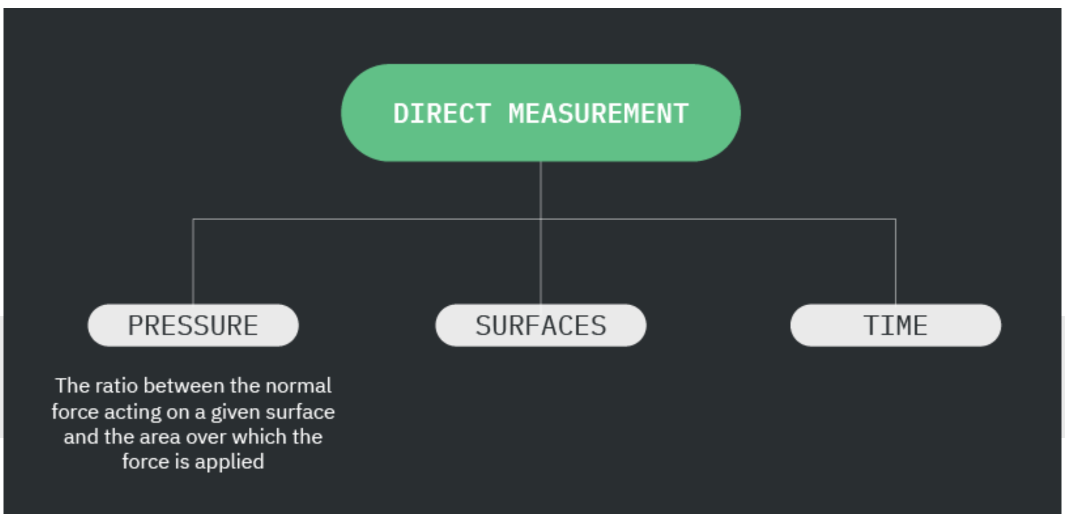


Table 1. Types of data directly measured by pressure mapping systems

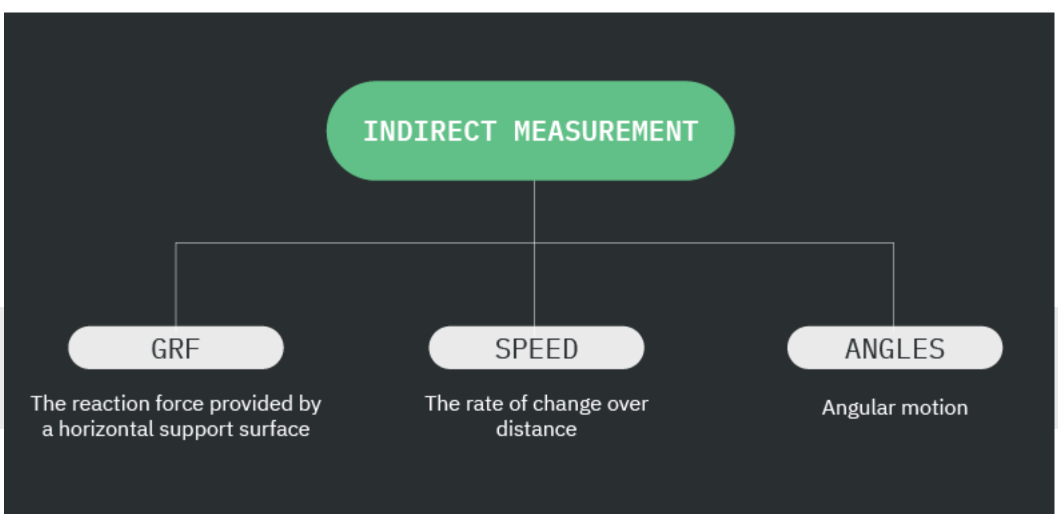


Table 2. Types of data indirectly measured by pressure mapping systems

With this in mind, let's look at the technology behind these systems. Technological factors can be divided into the following three categories:

- **Sensor Type**: Refers to the actual sensor being used in a given system.
- **Sensor Characteristics**: Refers to all the specific parameters related to how accurate the measurement is going to be.
- **Technical Specifications**: Refers to a series of characteristics associated with the management, quality and transmission of data.

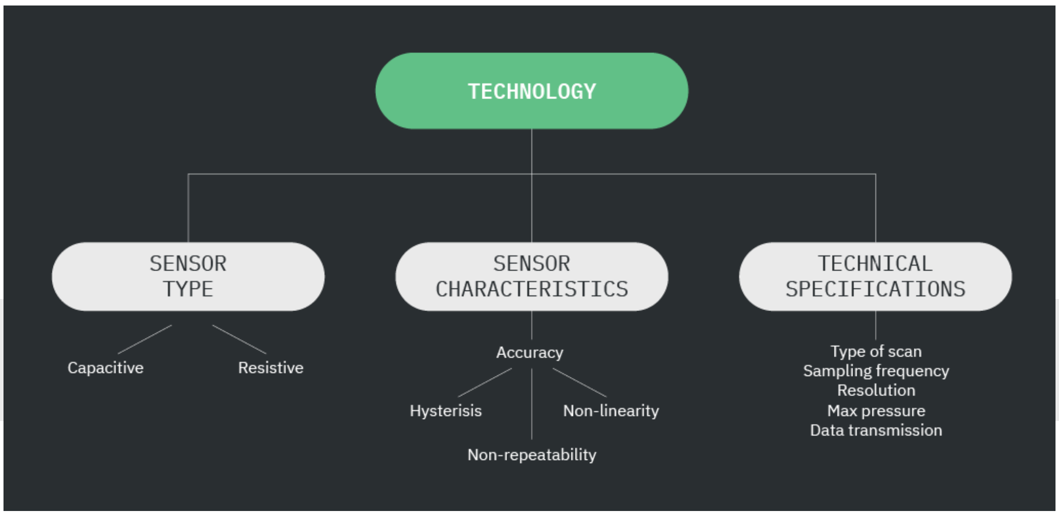


Table 3. Technological aspects of plantar pressure mapping systems

Sensor Type

There are different types of sensors used for plantar pressure measurement. We'll be focusing on the two most commonly used: capacitive and resistive.

Capacitive sensors, also called capacitance transducers, are characterized by two thin plates made of an electrically charged conductive material. The two plates are separated by an insulating elastic layer, called the *dielectric* layer, which bends once a force is applied, causing the two plates to compress.

The compression shortens the distance between the plates while the capacitance increases, and the change in voltage is what's measured.

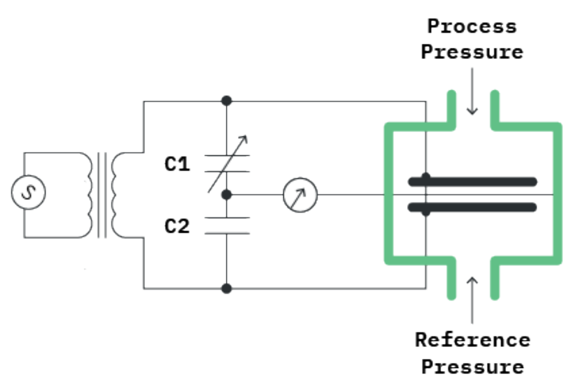


Figure 1. Example of capacitive sensor

Resistive sensors are made of a conductive film encapsulated between two electrodes.[3] The most used sensor in this category is the Force-Sensing Resistor (FSR), which is made of a conductive polymer layer that decreases its resistance when pressure is applied, causing an increase in current through the resistive sensors.

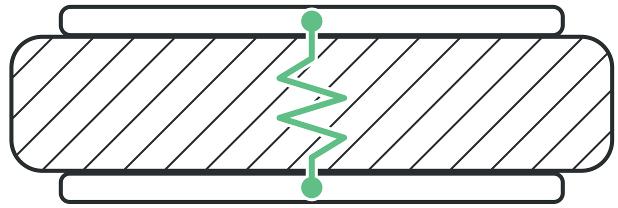


Figure 2. Example of resistive sensor

The main advantage of using capacitive transducers is that it allows for a precise quantitative assessment of plantar pressure, because the calibration curve is developed for each individual sensor in the matrix.[4] XSENSOR pressure measurement systems, for example, use capacitive sensors.

Sensor Characteristics

To define the level of accuracy of a pressure sensing transducer, there are three main parameters to be taken into account: *hysteresis*, *non-linearity,* and *non-repeatability*.

The overall accuracy of a sensor can be defined as the maximum deviation of a value measured by the sensor from the ideal value in a state of controlled conditions.

Hysteresis is the difference in the output signal of the sensor when it is being steadily loaded and unloaded.

Non-linearity is the largest deviation of the measured curve from a reference straight line; it is the sensor's response to the pressure being applied and shows the level of simplicity of the signal processing circuitry.[5]

Non-repeatability is the extent of variation in the output signals of different subsequent measurements of the same pressure.

A small non-repeatability error (i.e. high repeatability) is a fundamental characteristic for plantar pressure measurement systems.

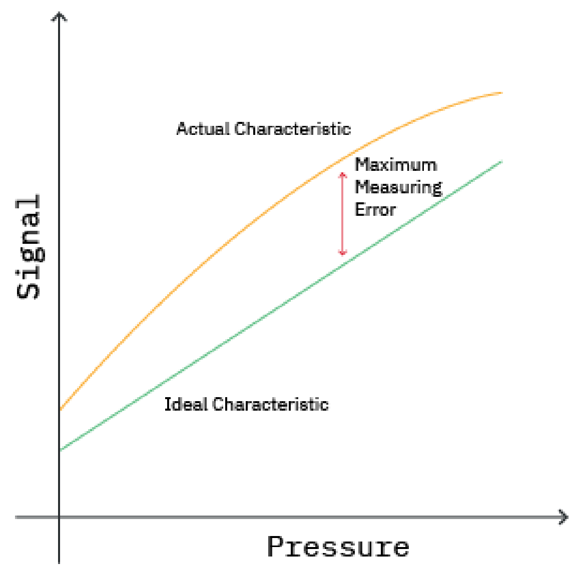


Figure 3. Accuracy of a sensor

Technical Specifications

The last category covers the characteristics associated with the management, quality, and transmission of data, such as:

- Type of scan
- Sampling frequency
- Resolution
- Max pressure
- Data transmission

The type of scan describes how the data is being acquired, like how the sensors are positioned.

The scan can be performed either through individual transducers positioned in different anatomical locations along the sole of the foot (discrete measurement), or through a series of sensors arranged in rows and columns.[3]

The latter is called matrix measurement and it's the most suitable type of scan for foot pressure mapping applications in sport because it allows the assessment of pressure distribution over the entire foot without sacrificing any anatomical location.

Sampling frequency is the number of samples per second measured by each sensor and it is usually expressed in hertz (Hz) or frames per second (fps). It can be considered a measure of the temporal resolution of the system.[3]

Resolution is a parameter associated with the total number of sensors as well as their size: a large number of sensors equals a high resolution and it is a measure of the spatial resolution of the system.

Max pressure refers to the actual maximum pressure value that a sensor can measure within the specific pressure range of the system.

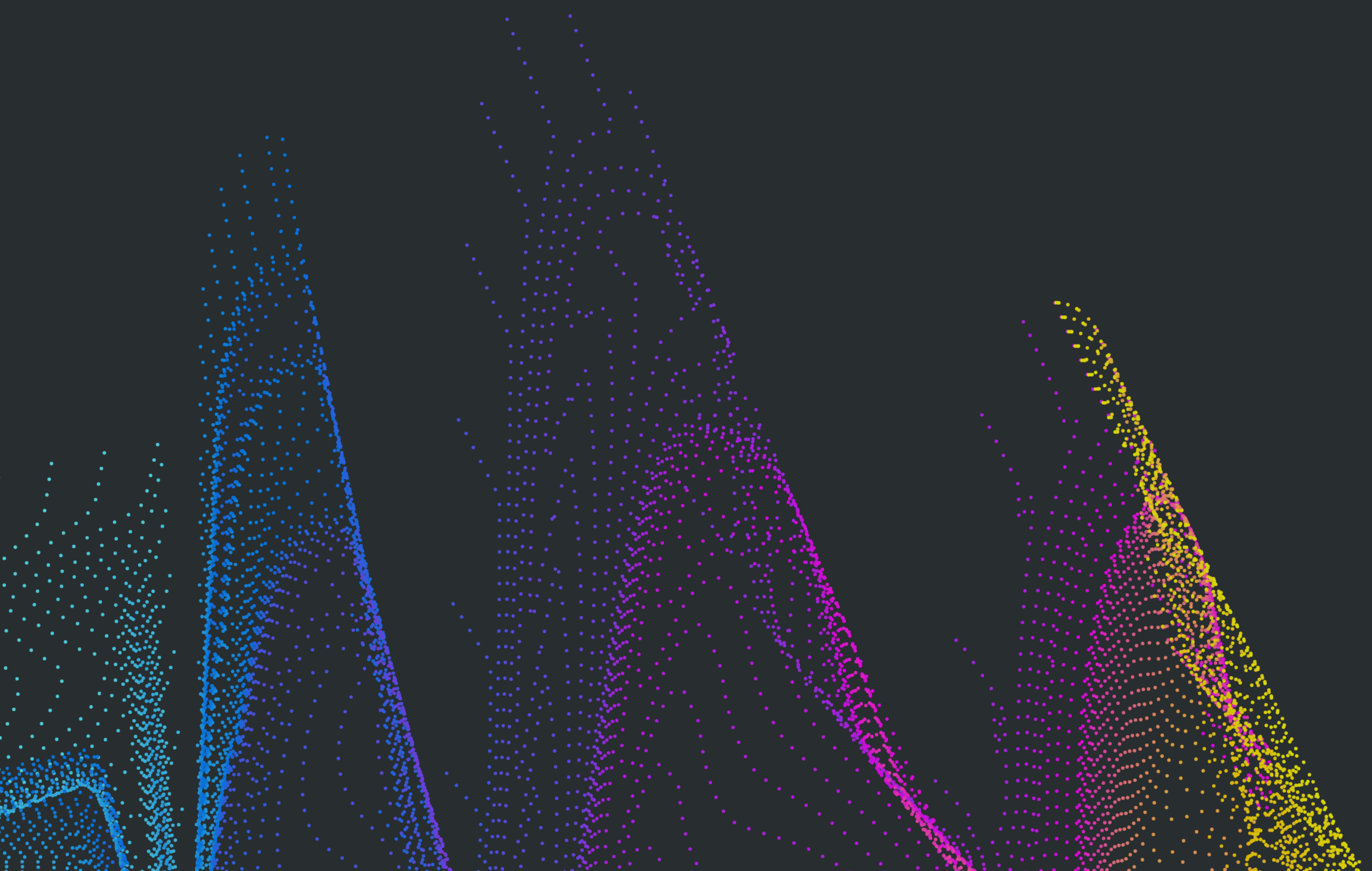
Data transmission is a fundamental component of foot pressure mapping in sports, especially when using in-shoe measurement systems. There are two main modes: wireless transmission and live streaming.

Wireless allows us to measure sport-specific movements and high-speed running with no cabling limitations, making motion more biomechanically efficient. Live streaming allows the coach to assess and potentially correct an athlete's movement in real-time thanks to live biofeedback options.

Now that we've covered the technology behind plantar pressure measurement systems, we can move on to the basic biomechanical concepts of pressure and force.

CHAPTER

02. Basic Biomechanics: Force and Pressure



Basic Biomechanics: Force and Pressure

In terms of physics, understanding the difference between *force* and *pressure* can help biomechanics professionals understand the advantages of using plantar pressure mapping with their subjects.

What is human movement?

The ability of an individual to move their body mass, causing a displacement of the centre of mass (CoM). Human movement is subjected to the main constraints represented by the laws of physics.

In biomechanics, displacement (*d*) is the change in position of an individual and it is described in reference to the spatial aspect of motion.[6]

The center of mass, also known as center of gravity, is the point representing the total weight over mass distribution of a body.[7]

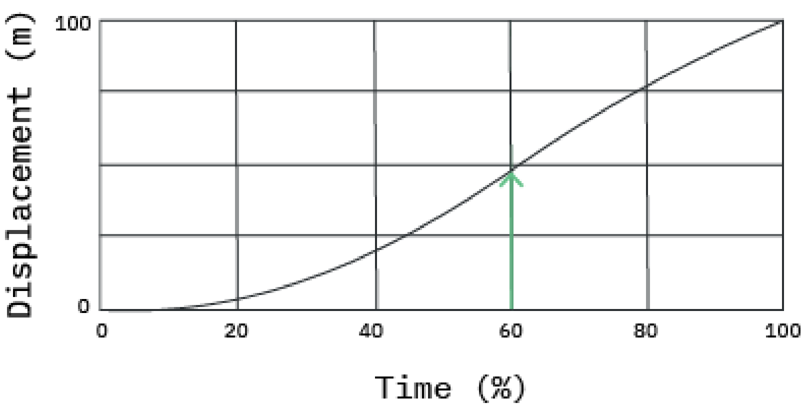


Figure 4. A displacement-time graph showing the horizontal displacement of the center of mass of a sprinter over time (from Bartlett, 2007)

There are three necessary components in the process of control and execution of human movement, which work together and follow a hierarchy:

1. Central Nervous System
2. Neuromuscular System
3. Force

We can define human movement as the result of "how the nervous system controls the actions of muscles to exert forces on their surroundings and thereby produce movement". [6]

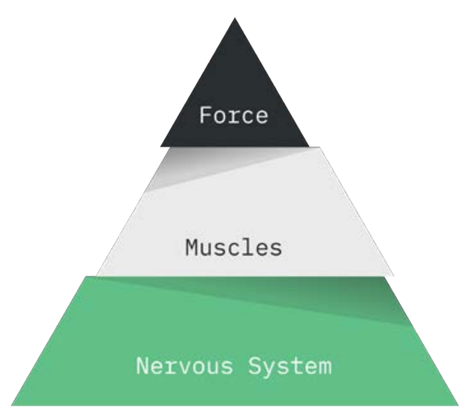


Figure 5. The hierarchical process of human movement

Basic Biomechanics: Kinetics and Kinematics

Together, kinetics and kinematics are the areas of study in physics that deal with the motion of an object. When analyzing movement and describing why and how motion happens, we need to understand the difference between them.

Kinetics studies the underlying causes of motion itself (why motion happens), while kinematics is concerned with describing human motion (how motion happens). Kinematics is focused on the mathematical description of motion that doesn't refer to forces.

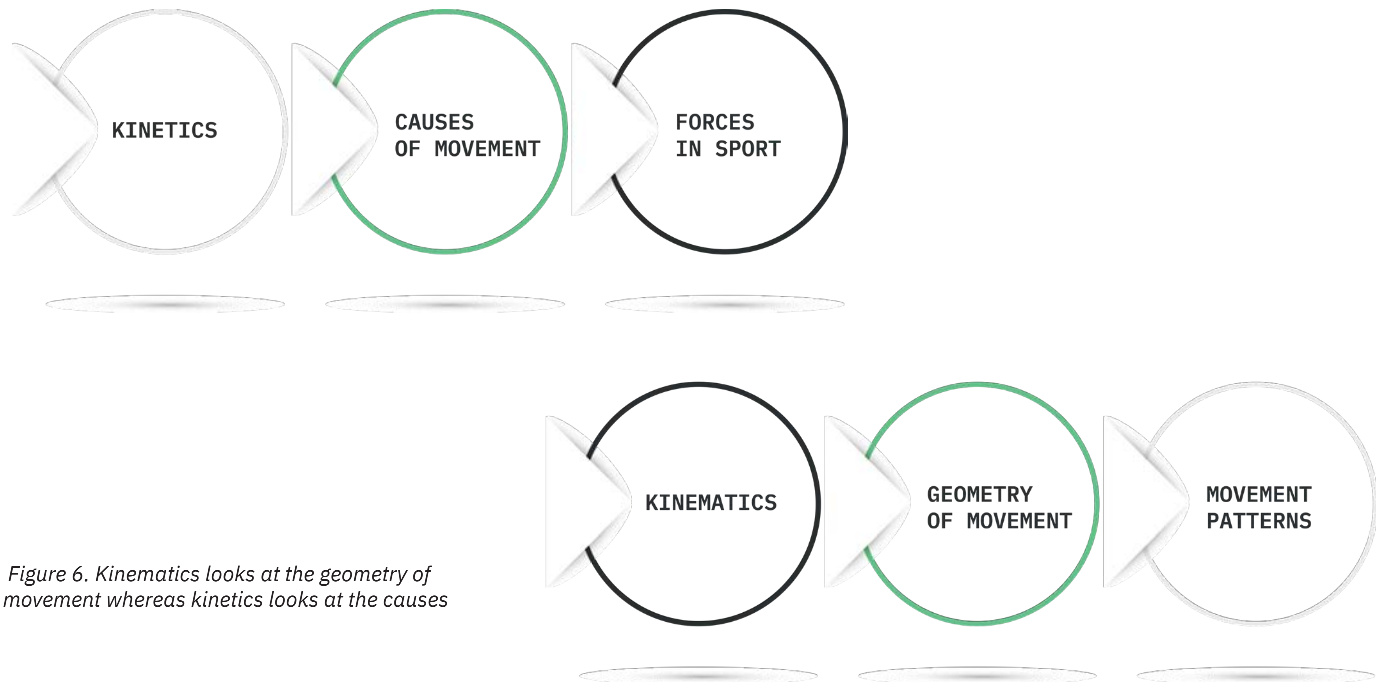


Figure 6. Kinematics looks at the geometry of movement whereas kinetics looks at the causes

Force and Pressure

In this context, both force (F) and pressure (p) need to be viewed through the lens of kinetics.

Force and pressure represent two complementary metrics that can provide in-depth insight into various aspects of human performance, as well as help prevent injuries and individualize training.

In physics terms, force (F) represents a vector quantity, meaning it has a size and a direction; on the other hand, pressure (p) is a scalar quantity because it is defined only by a single number representing its magnitude.

Force is defined as a straight-line push or pull, usually expressed in pounds (lbs) or Newtons (N)". [7] It is the effect of an interaction between two bodies.

Pressure is defined as an external force divided by the area over which the force acts; it is expressed in Pascal (Pa), which corresponds to one Newton per square metre (N/m^2). It is the ratio between the normal force acting on a given surface and the area over which this force is applied.

Pressure doesn't have a specific direction and even if you change the orientation of the surface over which a force is acting, this will cause a change in the normal force (the force acting at right angles to the surfaces of objects that are in contact) but not in pressure, which will remain the same.

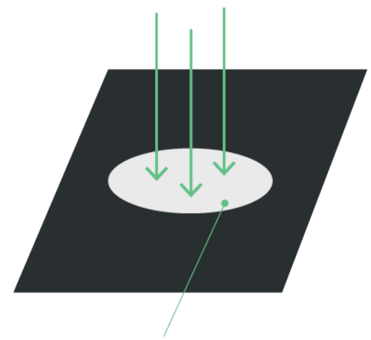


Figure 7. Pressure is Force x Unit Area

Understanding a Force (Pressure) vs Time Curve

Movements occur over time so it's important to understand what a force-time curve (or pressure-time curve) is, how to properly interpret it, and how to recognize the different phases of motion.

A force-time curve is a graphical representation where an applied force (in Newtons) is plotted on the x-axis and time (usually expressed in seconds) is plotted on the y-axis.

The graph allows you to analyze the mechanical effect of force acting over time (impulse) as well as recognize how force is being applied in different phases of motion through changes in momentum (and velocity).

Momentum can be defined as the overall quantity of motion possessed by a rigid body and it's measured "by the product of its mass and the velocity of its centre of mass".[8]

Since impulse and momentum are two variables related to each other due to the impulse-momentum relationship, then the proper analysis of a force-time graph is critical in understanding performance as it relates to velocity and acceleration, and how they relate to phases of motion (i.e. gait and running cycle).

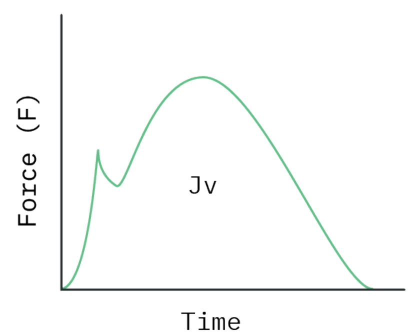


Figure 8. A simple force-time graph showing Force (y-Axis) and time (x-Axis) as well as impulse of a foot strike in running (from Knudson, 2007)

The impulse-momentum relationship states that "a change in momentum of an object is equal to the impulse of the resultant force in that direction", [7] meaning a large impulse is required to produce a large corresponding change of momentum.

The force-time relationship becomes particularly important in competitive sports, where the ability to produce more force in less time or a constant force over longer periods of time can be a determining factor in success.

In the next chapter, we will look at how pressure-time graphs collected by plantar pressure measurement systems can help in assessing human movement and performance.

TERM	DEFINITION
CoM (Center of Mass)	The point that represents the total weight over mass distribution of a body. The point about which the mass of a system is evenly distributed.
CoP (Center of Pressure)	The point of application of the ground reaction force. The location of the GRF vector.
CoG (Center of Gravity)	See Center of Mass.
Force	Defined as a straight-line push or pull. It is the effect of an interaction between two bodies.
Pressure	Defined as an external force divided by the area over which the force acts. It is the ratio between the normal force acting on a given surface and the area over which this force is applied.
GRF (Ground Reaction Force)	The reaction forces created by pushing against the ground. (Knudson, 2007)
Momentum	The quantity of motion possessed by an object, a vector quantity. The products of mass x velocity.
Moment	Rotating effect of a force (torque).
Force-Time Curve	A graph representing the force that acts on a body in a certain amount of time.
Impulse	The area under a Force-Time graph (J = F * t).

Table 4. A summary of the basic biomechanical concepts introduced in this chapter

Center of Mass and Center of Pressure

Often confused for one another, Center of mass (CoM) and center of pressure (CoP) represent two different biomechanical aspects.

The center of mass is the point that represents the total weight over mass distribution of a body and the point “about which the mass of a system is evenly distributed”. [6]

The center of pressure is the point of application of the ground reaction force (i.e. the location of the GRF vector).

The projection of the vertical line from the CoM to the ground represents the center of gravity, and the trajectory of the CoP is totally independent of the CoM, meaning that their trajectories do not match each other, as shown in Figure 9.

The CoP adjusts its response and trajectory to prevent any shift in CoM from causing a fall or an abnormal posture; it can be defined as “the neuromuscular response to the imbalances of the body’s CoM”. [9]

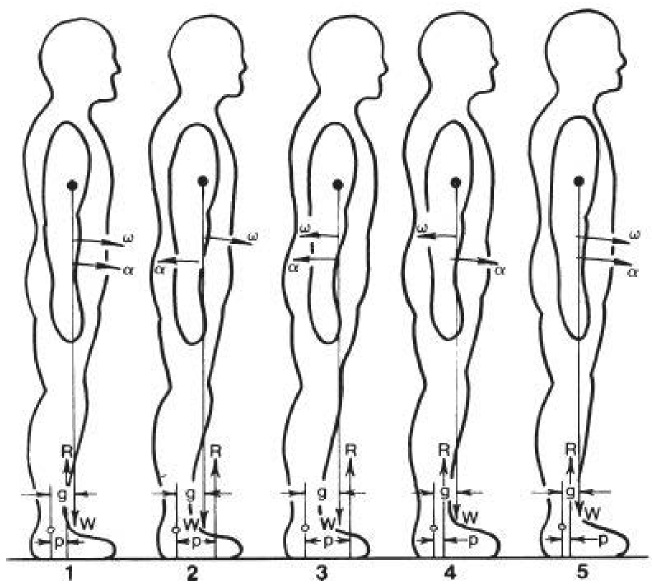
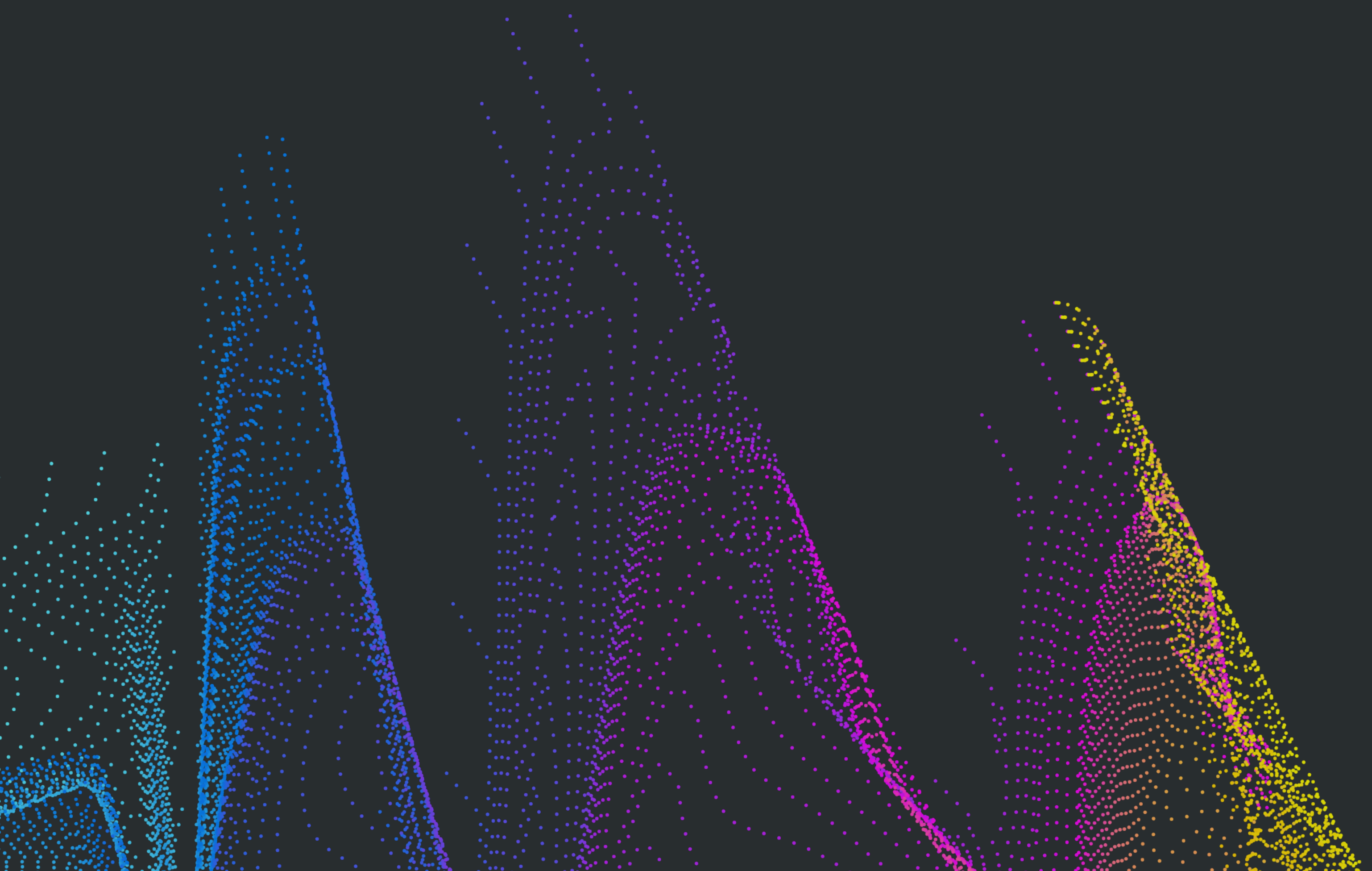


Figure 9. The difference between CoP and CoM showed during five different points in time of a human body swaying back and forth. The CoP is shown by the vector R and CoM by the vector W (from Wimter, 2009).

CHAPTER

03. Hardware and Software: Mats and Insoles



Hardware and Software: Mats and Insoles

When it comes to plantar pressure mapping technology, there are two hardware options that — when used together — measure the full spectrum of human performance factors.

Plantar pressure analysis can be performed either on a sensorized mat over which subjects can walk, run and sprint, or through a sensorized insole inserted directly into the shoe.

Though there are some similarities between the two products, there are some key differences, particularly in terms of methodology and analysis options.

Plantar Pressure Mats and Insoles: An Overview

It's no surprise that not all plantar pressure systems are made equal. In order to be successfully implemented in a sport performance environment, specific requirements need to be met.

When it comes to analyzing movement, lab researchers often have entirely different needs than coaches, rehab specialists and sport scientists. For lab research, the environment and settings need to be strictly controlled. For real-world testing, flexibility is more important.

For a plantar pressure system to be easily integrated into a sport science context, it must meet the requirements of a highly dynamic environment. That means it needs to provide precise, repeatable, and reliable data without being time-consuming to use or set up.

The following table illustrates the main features needed for a plantar pressure measurement system to be applied in a sport setting:

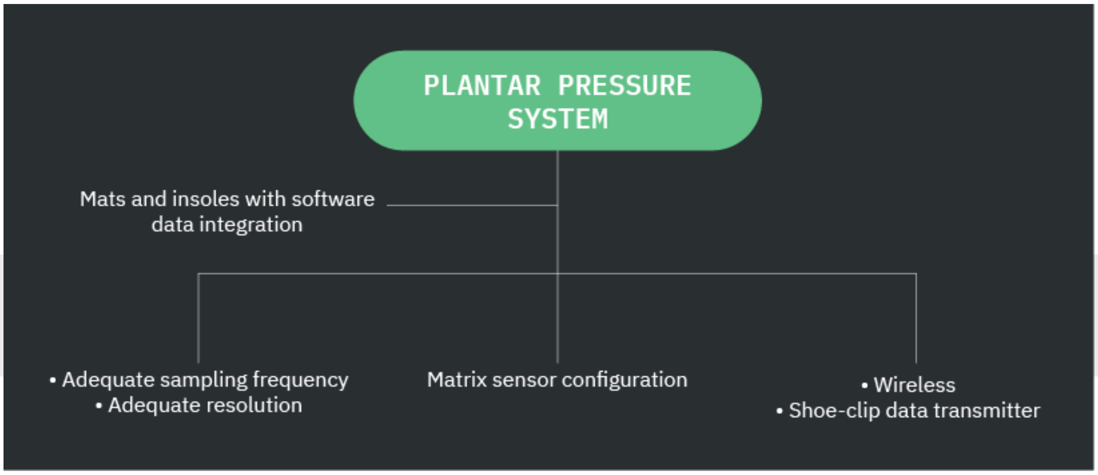


Table 5. The main features needed for a plantar pressure system in sport applications

When choosing a plantar pressure measurement system for sport applications, it's advantageous to find one that offers both a walkway mat and an in-shoe option. Each option meets different goals and testing requirements; together, the systems offer complementary datasets. Depending on your budget, you might prefer to start with one type of hardware and then add the second one later on. Choosing a manufacturer that produces both systems will help ensure proper data integration and workflow between the different sets of hardware.

To properly capture the high-speed movements of sporting activities, an adequate resolution and sampling frequency is needed. Resolution refers to the number of sensels (the individual pressure measurement units) and it affects the quality of the footprint image. Sampling frequency refers to the amount of information being captured every second.

The matrix configuration of the sensors is critical in measuring pressure distribution simultaneously over the entire plantar surface, rather than the discrete measurement technology where individual sensors are positioned in different anatomical landmarks over the plantar surface.[10]

Lastly, wireless capability is a key feature for an in-shoe system as this maintains freedom of movement without altering natural biomechanical patterns.

Walkway Sensor: Characteristics and Specifications

The XSENSOR Walkway Sensor is a pressure mat with a total area of 104” x 28” (264cm x 71cm) and a sensing area of 95” x 20” (243cm x 51cm).

It uses capacitive sensor technology with more than 7500 active sensors, and has a pressure range of 1-128 psi (0.67-88 N/cm^2).

The walkway, with its large sensing area and ultra-low profile (thickness of <1.5 mm) allows you to measure walking and running gait without affecting the natural pattern of each stride.

Proper technology application in sport requires not only high-quality hardware and software, but also ease of installation and adaptability to the environment — this means being able to move the system around as needed and set it up as quickly as possible.

The Walkway has a flexible structure so it can adapt to any surface and it can be rolled or folded, making it easy to carry.

Figure 10. The XSENSOR Walkway mat

X4 Intelligent Insoles: Characteristics and Specifications

X4 Intelligent Insoles are an integrated system made up of sensorized insoles, data transmission electronics, and software.

Each insole has a high resolution of 230 sensels with a pressure range of 1-128 psi (0.67-88 N/cm^2). A sensel is the single pressure measurement unit and the amount of sensels available in a system determines its resolution: the higher the number of sensels, the higher the resolution of the system and the better the footprint image will be.

The system is completely wireless, uses bluetooth transmission and the electronics attach directly to the shoes, minimizing any negative impact on the fluidity of movement — an important factor when analyzing a sport-specific task.

The below tables show the system specifications:

Figure 11. The X4 Intelligent Insoles

INSOLE SENSOR	
Accuracy:	± 5%
Thickness:	< 2.0 mm
Pressure Range:	1-128 psi, 0.7-88.3 N/cm^2
Resolution:	6.5 mm (233 sensels/sensor)

ELECTRONICS - ON-SHOE	
Sampling Rate:	150 hz
Wireless:	Bluetooth
Memory:	16 GB (7.5 hrs recording)
Size:	1.7 cm x 4 cm x 5.5 cm
Weight:	42 g

Table 6. X4 Intelligent Insole System Specifications

Software: Measurement and Analysis

At the core of the X4 Intelligent Insole system is the Pro Foot & Gait software, powered by the Intelligent Dynamic Sensing platform. An athlete-centered assessment system comprises four interconnected elements: measurement technology, analysis tools, the athlete, and the biomechanics professional.

Undetectable sensors measure the athlete's natural movements — without limitations — and data is wirelessly collected, making it easy for biomechanics professionals to coach athletes through a plantar pressure mapping session. After data capture, visual and statistical algorithms provide biomechanics professionals with the insights they need to advise athletes on the best way to minimize injury or maximize performance. The comprehensive software toolkit allows sports scientists to perform multiple analyses, both in real-time and after data capture.

Real-time visualizations offer a helpful biofeedback tool for rehabilitation, proprioception and technique training. Post-processing analysis allows review of the whole footprint, where you can:

- See peak and average pressure values,
- Separate force-time and pressure-time curves for each foot segment
- Analyze the trail of the center of pressure
- Visualize spatio-temporal characteristics of gait
- Compare different stances over time

Let's look at the hardware options in more detail in the next section.

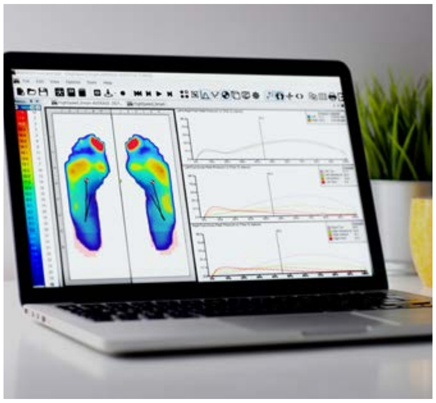


Figure 12. Hardware, software, athletes, and biomechanics professionals working in tandem offers an athlete-centred approach.

Walkway and Insoles: Methodological Differences in Sport Applications

Both walkway and insoles measure plantar pressure, but there are some methodological differences and each hardware suits a specific purpose.

The table below summarizes the different applications and methodologies for the walkway and insole sensors:

Comparison of Walkway Sensor and X4 Intelligent Insole System

WALKWAY SENSOR	X4 INTELLIGENT INSOLES
Walking gait (with and without shoes)	Running gait
Rehab and return to play	Sprinting analysis (linear sprint, acceleration, deceleration)
Biofeedback training	COD (Change of directions)
Shoe fitting and testing	Orthotics testing
Force/Pressure Analysis and Neuromuscular Stability	Force/Pressure Analysis and Neuromuscular Stability
	Spatio-temporal gait statistics

Table 7. Mat and insole applications in sport

Conclusion

In the first part of this ebook series, we introduced the basics of plantar pressure mapping technology, starting with origin and etymology. From there, we dove into the different types of sensors and their technical specifications.

We have also covered basic biomechanical concepts to help you understand human movement — including kinetics and kinematics — how to understand a force over time curve, and center of mass and center of pressure.

Last, we discussed XSENSOR hardware and software, particularly the X4 Intelligent Insole System and Walkway Sensor, and how each can be used to gain insights in sport applications for improving human performance and reducing risk of injury.

In the next ebook, we will cover:

- Foot pressure mapping applications in sport; and
- Practical protocols for testing and monitoring athletes based on different goals and needs.

For more information on the X4 Intelligent Insoles System or Walkway Sensor, visit xsensor.com or email us at sales@xsensor.com

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