



## **Portable Apparatus for Gait Analysis Based on Tactile Force Sensors**

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### **ABSTRACT:**

This article presents the authors' experience in the use of tactile force sensors (FSR) in the development of instruments tailored to the needs of physicians, gait analysis and dynamic analysis of plantar pressure and provide preliminary evidence of effectiveness of CALORCRO system in clinical practice for objective assessment of the gait degradation progress.

CALORCRO system novelty lies in the use of force tactile sensor FSR - FlexiForce type - and their location in the shoe sole, sensors that transmit information on the mechanical behaviour of various areas of the sole of the foot. The sole of this shoe has ten areas for placing force sensors. Sensors' location was defined as the dynamic pursuit of the foot. In order to avoid the phenomenon of noise, a mechanical puck was designed, so that sensors can be loaded only on their active surface and ground reaction forces exerted during gait, to be recorded throughout the plantar surface. Each sensor is calibrated in default increments – it was designed a special software for sensors calibration.

Based on experience with design, development and clinical testing of experimental model of the portable gait analysis CALORCRO device, research will be conducted for tactile force / pressure sensor application for plantar pressure determination. From analysis of plantar pressure values and its distribution, doctors will manage their most appropriate treatments for disorders of static plantar for diabetic foot, spastic foot, of rheumatoid arthritis foot, the plantar fasciitis and will prevent any diabetic foot lesions. Equally, plantar pressure value analysis and their distribution will be useful in customized manufacturing of tailored prostheses, in physical therapy programs establishing.

### **I. INTRODUCTION**

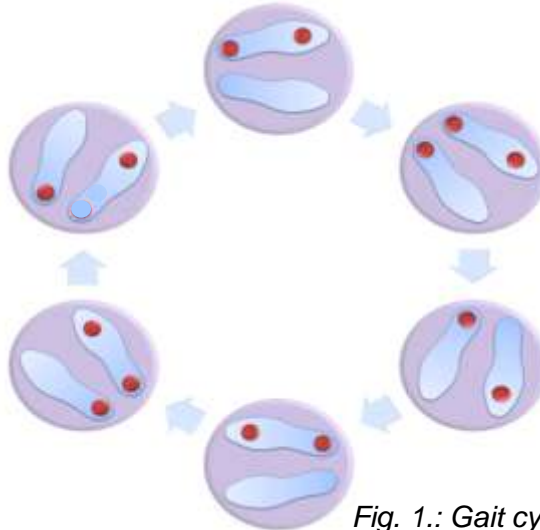
#### **A. Gait definition and assessment**

Gait is defined as the translation of the human body, simultaneously with rotational movements of its segments. It follows from the alternating legs movement while ensuring the maintenance of balance and propulsion [Outrequin, 1991]. This process is automatic and must respect several requirements:

- to propel the body forward (the main purpose of gait or frontal translation),
- to maintain the equilibrium in static and dynamic conditions;
- to coordinate the position and balance, it has adapted to the environmental constraints.

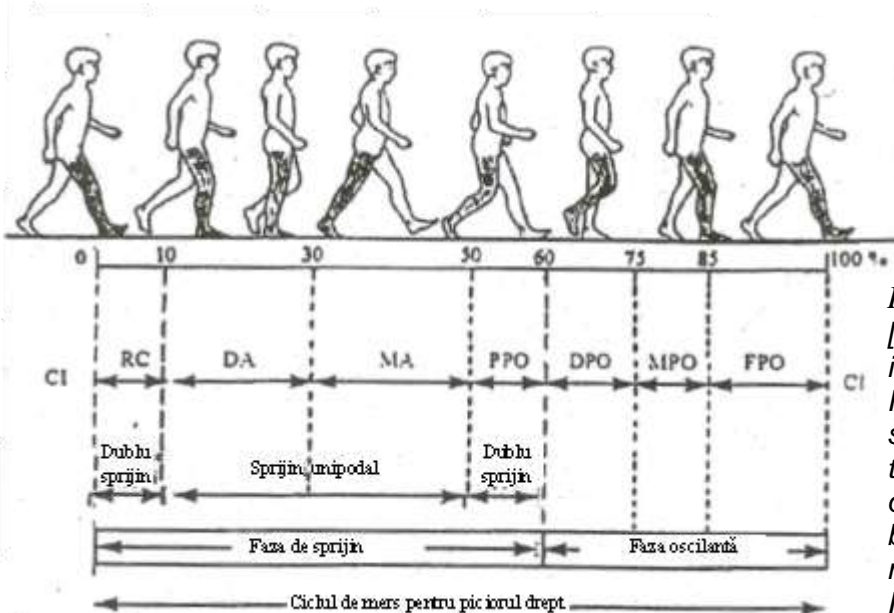
Gait, defined as **alternative bipedalism** has as measuring unit the **gait cycle** represented by the distance between the ground contact point of a foot and the immediately following ground contact point of the same foot. Simplifying, gait cycle consists of two symmetrical parts: when the right leg is moving and when left leg is moving - Figure 1. **Step** is defined as

the distance between the ground contact point of a leg and the ground contact point of the other leg. In the literature, several authors [Chao et al., 1983, Pierrot-Desseiligny and al, 1993] decompose gait cycle in two main phases, stance phase and balance phase.



*Fig. 1.: Gait cycle*

For a detailed study is considered that the gait cycle is subdivided into eight phases, five of which are taking place during stance phase and three during the balance phase (Figure 2.).



*Fig. 2.: Gait cycle [Cottalorda and 1999]. CI: initial contact (heel impact), RC: loading response, DA: stance start, MA: middle of the stance; PPO: pre-phase of balance, DPO: early balance phase, MPO: middle balance phase, FPO: end of balance phase.*

The proportion between the stance phase and the balance phase during a gait cycle varies depending on gait speed, being for the normal gait: 60% for stance and 40% for balance. The stance is the contact phase with the ground - sequences: CI, RC, DA, MA, PPO. Balance is the phase in which the foot don't touch the ground - sequences: DPO, MPO, FPO. Gait assessment involves **kinematic analysis** (take into consideration the spatial-temporal parameters:

length and cycle time, length and duration of stance and balance phases, stride length, cadence, gait speed), **kinetics** (take into account the forces that develop during gait - the forces are measured in three axes: vertical  $F_z$  as sagittal, posterior-anterior  $F_y$  and transversal as medial-lateral  $F_x$ ), **plantar pressures appearance** which develops in the contact (give information on the role of the leg during the stance phase on ground [Gaviria 1994; Giacomozzi, 2000]).

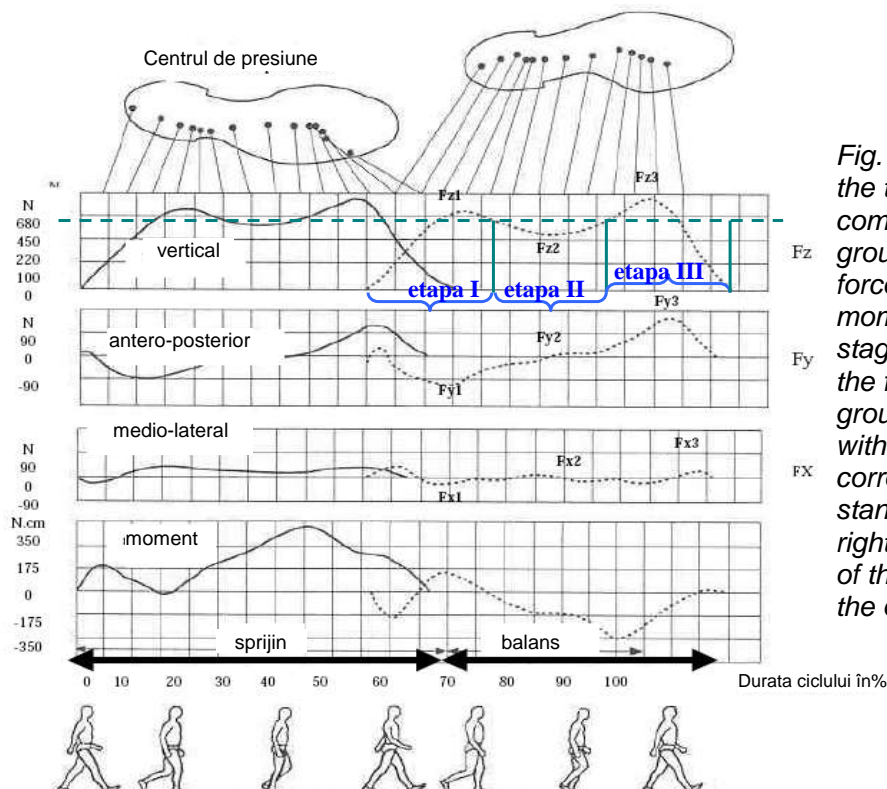
Type curves of component forces  $F_x$ ,  $F_y$ ,  $F_z$  which are obtained during recordings (with fixed systems - force platform - or ambulatory systems) during gait are represented in Figure 3.

Vertical force supported during the stance phase is characterized by 2 successive peaks ( $F_{z1}$  and  $F_{z3}$ ) separated by a decrease ( $F_{z2}$ ).  $F_{z1}$  occurs in the acceptance phase, during which the body weight and its kinetic energy are transferred to the leg.  $F_{z2}$  occurs in the moment when the body centre of gravity is changed. During this period the subject applied to one leg slightly less than its weight.

$F_{z3}$  represents the preparation of the next step that comes back to accelerate the centre of gravity and increase the gravity energy.

Posterior-anterior force: has initially a small negative peak ( $F_{y1}$ ) which corresponds to the heel impact and to the brake force directed towards. This decreases and cancels in the middle of the contact phase ( $F_{y2}$ ) to become, after that, a propulsive force ( $F_{y3}$ ).

Medial-lateral force: contains a short negative peak ( $F_{x1}$ ) in the lateral direction at the moment of contact, because the leg is pulled inwards. For a short period the force is aligned with the leg axle ( $F_{x2}$ ). During the rest of the contact the force is essentially positive ( $F_{x3}$ ). Normally expressed in Newton (N), these forces are reported to the weight of the subject (Body Weight or BW) in order to make inter-individual comparisons.



*Fig. 3. The results of the three components of ground reaction force. Vertical axis moment. Contact stages of the sole of the foot on the ground. The routes with continuous line corresponding to the stance phase of the right leg. The weight of the subject is of the order of 600 N*

## B. Tactile force sensors - FSR

In clinical research laboratories the measurement and classification of human movement involves the use of a set of sensors and transducers.

Sensors and transducers provide qualitative and quantitative information about gait mechanics and about movement in general, kinematic and kinetic data, values of the reaction forces at foot contact with the ground, the energetic consumption.

Tactile sensors are contact sensors that allow their positioning in very narrow spaces and having often very complex geometries. A force **piezo-resistive sensor - FSR** (Fig. 4.) can be achieved in various ways within a very thin and flexible printed circuit.

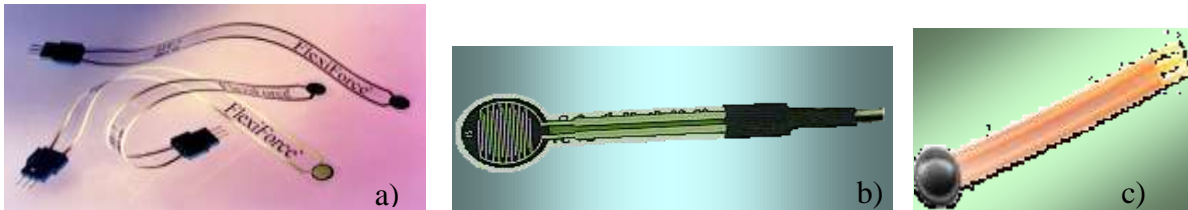


Fig. 4.: Resistive tactile sensors - FSR: a) the concept **FlexiForce Tekscan**, USA, b) the concept **Interlink**, USA, c) the concept **CUI Stack**, USA.

FlexiForce sensor is made by laminating two flexible and very thin films (thickness 0.008 inch) made of polyester / polyamide, each of them is re-covered with a silver film which serves as a conductor on the one hand and as electrodes that define the geometry of the sensitive area on the other hand. Between the two circular silver electrodes is inserted a pressure sensitive layer made of special ink. When the sensor is unloaded its resistance is very high. If on the sensor a force is applied, its strength decreases, as shown in Figure 5. FSR sensors are sensitive and have cvasiliniar behaviour.

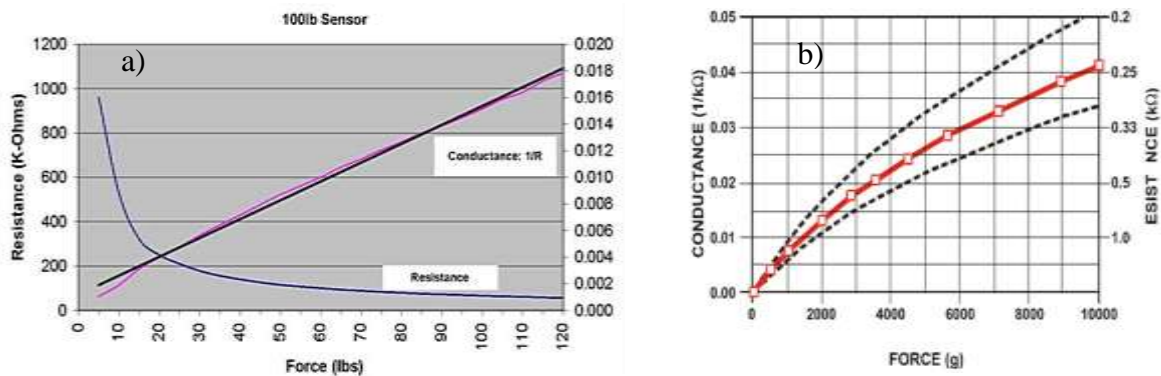


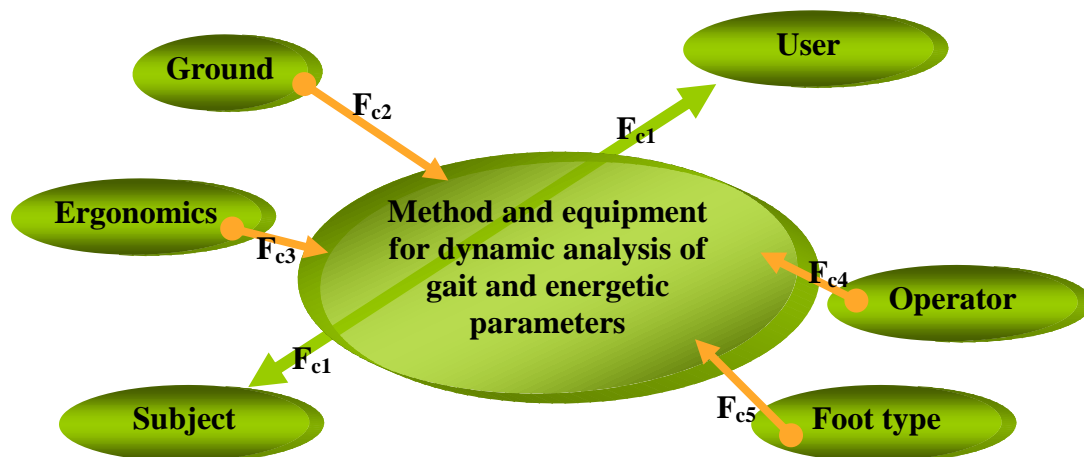
Fig. 5.: Curve of resistance / conductance changing by the applied force: a) for FlexiForce sensor, Tekscan, b) for Interlink FSR sensor

## II. CALORCRO SYSTEM ACHIEVEMENT

Our work aimed to create a portable gait analysis system which is simple, reliable, mobile, accessible as well technical and financial, for use in natural walking conditions, allowing the receiving of objective and exploited data regarding the descriptive parameters of gait and the energy parameters.

The idea was to design a system to retrieve information that the foot is able to give during contact with the ground. If the system could be in direct contact with the ground, then we can analyze the main **spatial-temporal parameters**, **ground reaction forces** and **energetic parameters**. It was thus able to propose a study of gait. If this tool could be placed in a shoe and could be independent of any analysis system nearby, then it is able to be used under natural gait.

In Figure 6 are shown requirements and demands that had led to the achieved equipment:  $F_{c1}$  main function - allows measuring and observing the evolution of walking subject,  $F_{c2}$  - must be adapted to normal environment and be used on any type of tough ground,  $F_{c3}$  - must be adapted to the human body and not bother walking;  $F_{c4}$  - must be easy to be used and not require special skills;  $F_{c5}$  - must be adapted to any type of foot (size, flat foot, hollow foot, etc.)



*Fig. 6.: Requirements and demands of the proposed system functions*

Value of this equipment, named CALORCRO, is given both by the **type and quality of the sensors** and its endowment with **informatics and performing software**.

**The novelty of the system** (Figure 7) lies in the use of force tactile sensor FSR - FlexiForce type - and their **location** in the shoe sole, sensors that transmit information on the mechanical behaviour of various areas of the sole of the foot.

The sole of this shoe has ten areas for placing force sensors.

Sensors location was defined according with the **dynamic pursuit of the foot**. In order to avoid the phenomenon of noise a mechanical part - pill / puck was developed - (Figure 7).

In this way the sensors can be loaded only on their active surface and the **reaction forces on ground, occurred during the gait, can be recorded throughout plantar surface**.

Each sensor is calibrated in default increments (Figure 8) - it was designed special software for sensors calibration.

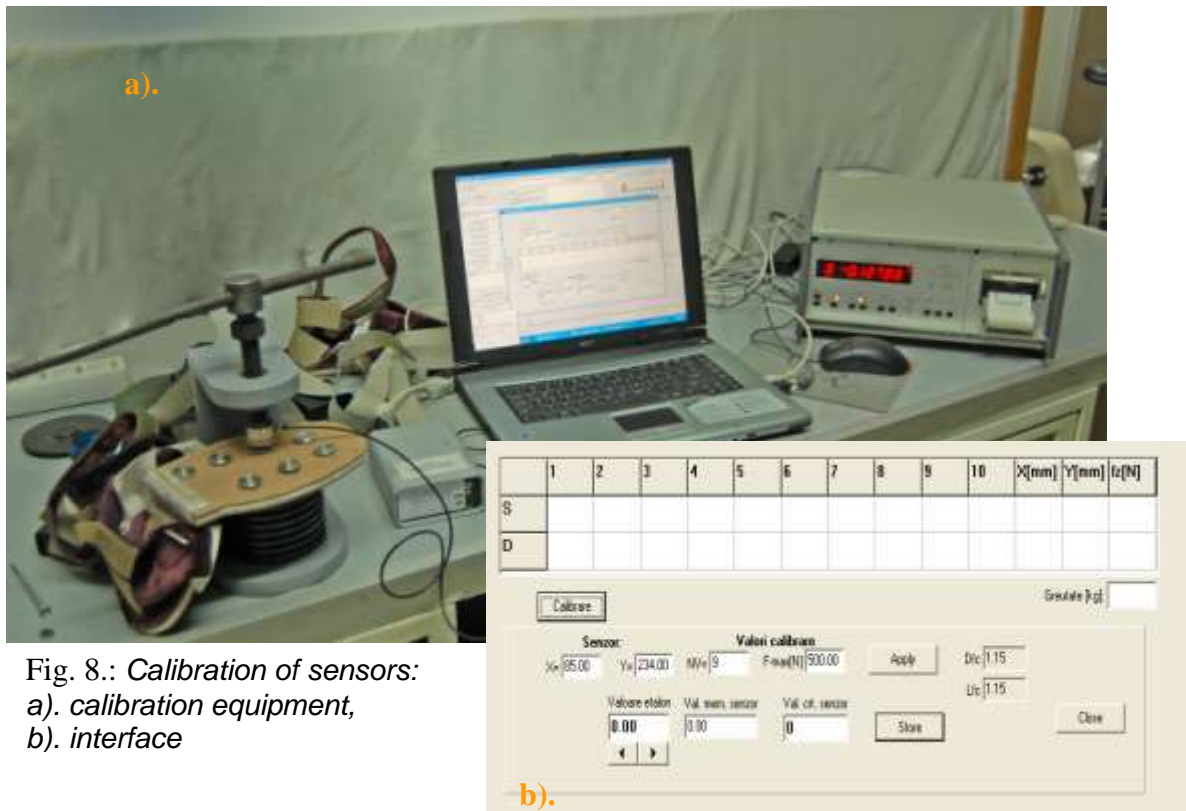
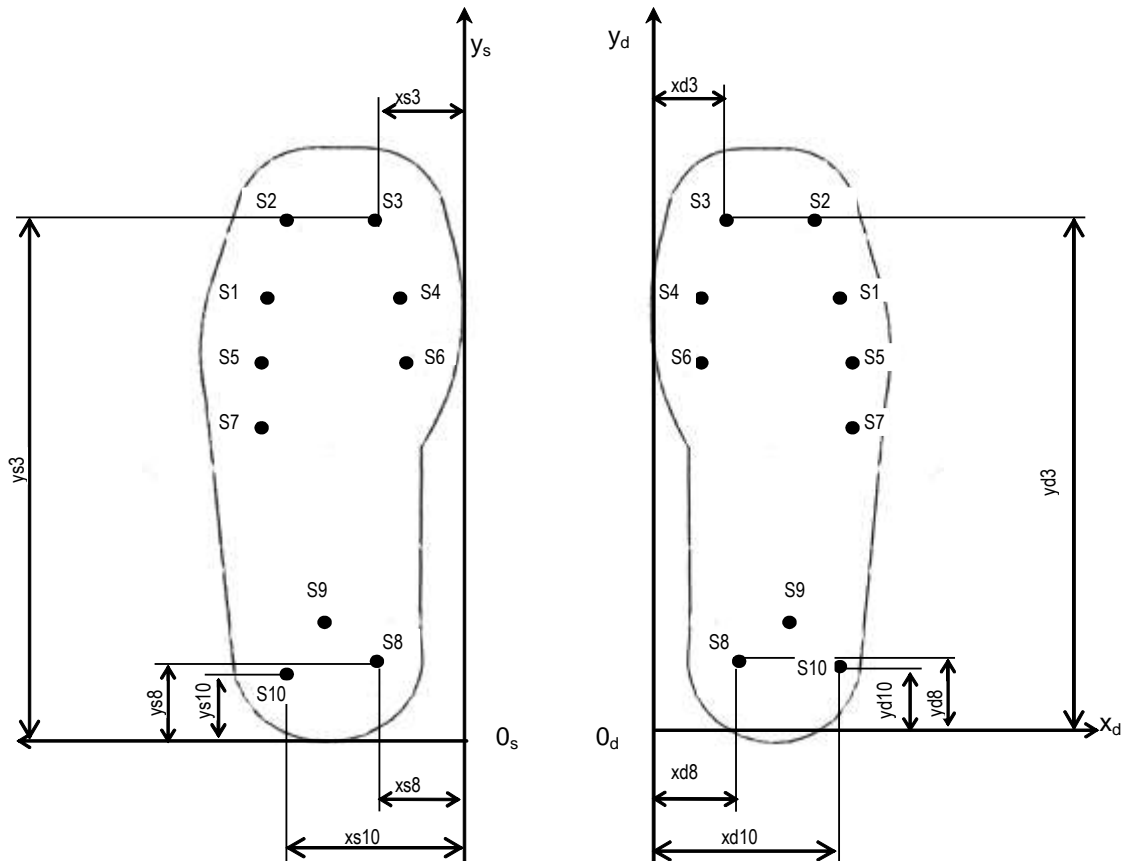


Fig. 8.: Calibration of sensors:  
 a). calibration equipment,  
 b). interface

The subject, equipped with CALORCRO system, can move freely because the sensors **don't require an origin** – the system's algorithm determines the successive position of application point of vertical force of ground reaction, the areas, where sensors are placed in the sole, are

defined by a pair of coordinates expressed in millimetres:  $x_s$ ,  $y_s$ , respectively  $x_d$ ,  $y_d$  (Figure 9). Thus the ground reaction forces, occurred during the gait, can be recorded and located over whole plantar surface. The sensors' response is linear and absolute error is less than 5% if on each sensor a stable force is loaded.



*Fig. 9: Defining the sensors' location*

The specific software developed for this application allows detailed and objective analysis of gait of healthy and injured / ill subjects, by:

- measuring the vertical force of ground reaction for each leg separately;
- measuring the total vertical force of ground reaction;
- measuring the anterior-posterior force;
- measuring the energetic consumption;
- measuring the spatial-temporal parameters.

### III. PLANTAR PRESSURE ANALYSIS NEED

**Plantar pressures** are closely related to the **ground reaction forces**. They represent the force per area unit. At the comfortable speed, the foot is on the ground for a variable period between 0.20 and 0.30 seconds, that makes impossible the clinical observation. The dynamic analysis must take into account this quick active phenomenon.

**Plantar pressures give us information on the leg's role during the stance phase of**



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**support on ground** [Gaviria 1994; Giacomozzi, 2000].

This phase of support on the ground allows the disclosure of a large number of gait defects **revealed by the doctor from a damaged support.**

**The values and the plantar pressures distribution** present interest in terms of analysis and treatment of pathological problems associated to neuromuscular and / or skeletal systems [Pite, 1996, Lord, 1997; Ahroni, 1998, Hughes, 2000; Lobmann and, in 2001, Maluf, 2001 and Morley, 2001]: the prescription of orthosis, of plantar supports, the establishment of kineto-therapy programs, the limitation of support on the affected extremity.

The leg as a whole, as an anatomical part, plays three roles: the amortization, the balance and the propulsion roles.

Foot contact with the ground is made in three phases (Figure 3):

• **Phase I - contact at the heel level**

**The contact at the heel level** takes place from the first recording of ground reaction force  $F_z$  up to the moment when  $F_z$  becomes for the second time equal to  $G$  (the weight of the subject measured in N). The movement follows an arch having the radius equal to the radius of calcaneus bone + damper tissue assembly.

The heel area which is available for impact is extremely low: on average  $23 \text{ cm}^2$  for the entire heel and only  $15 \text{ cm}^2$  for calcaneus. Calculated pressures are great, but the compression time is very short (3% of stance phase). The repeated impacts (between 1000 and 1300 for a walking of one kilometre) and the intensity of aggression on the heel (from 120 to 160% of body weight -  $F_{z1}$  in Fig. 4.5.) can give the size of the possible cumulative trauma.

• **Phase II – the whole sole is in touch with the ground**

Almost instantly the foot moves to its external side, which favours the dispersion of pressure. The assembly of foot bones shows the existence of curves on its external edge. This arch made of not-deformable tissue is better adapted for a steady support than the inner part of the foot, composed by deformable muscle tissue. The migration of pressures recorded under the foot shows a predominance of support on the external area, which is involved in both the **balance and propulsion** [Pelissier, 1997].

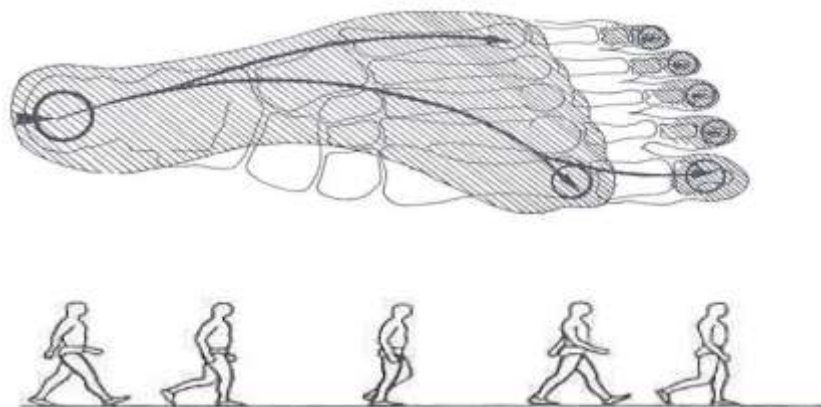
**The contact of the whole foot on the ground** takes place around the moments when the normal reaction of the ground  $F_z$  is equal to the subject's weight (Figure 3.). Throughout this period  $F_z \leq G$ .

• **Phase III – the phalanges contact with the ground**

While the heel is rising, the subject compresses the flexors tendons. The vertical projection of body weight falls on the vertical of metatarsals joints - in this phase  $F_z \geq G$  ( $F_{z3}$  in Figure 4.5.) and there, practically, only the examined foot is on the ground. The migration of plantar pressures occurs, finally, through halux (thumb) - in this phase  $F_z \leq G$ , the body weight is transferred then to the contralateral leg.

Figure 10 is an example of representation of the plantar contact areas for a healthy subject, occurred during the stance phase of the gait cycle. The movement of the support points of the foot is also called **the pressure centre movement** [Alexander, 1990; McPoil and, in 1999, Orlin and McPoil, 2000; Cottalorda, 1999, Claeys, 1983].

The support area of the loaded foot is first the heel, then it moves along the external edge of the foot to the ends of metatarsals, to be found finally, during the last phase, in the halux phalange.



*Fig.10.: Distribution of successive support points at the foot level during the stance phase of walking (Allard 2000).*

#### IV. CONCLUSIONS AND PERSPECTIVES

After the achievement, the CALORCRO system was tested on healthy subjects as well as on patients. Starting from the set of data recorded during the tests for two groups of subjects - patients and healthy subjects - we analyzed the relevance of the tests by ROC method (Receiver Operating Characteristic). It should be established whether the recorded variables: the gait speed (m / s), the steps' length (cm), the frequency of steps (Hz), the duration of stance phase for each leg related to the step duration (%), the ratio of vertical external power and product: subject's mass x advance speed (W / (kg.m / s)), the ratio of total external power and product: subject's mass x advance speed (W / (kg.m / s)) can distinguish one healthy subject from a patient. **The obtained results were very encouraging and reinforced the idea that the use of tactile force sensors for taking over primary information regarding the measured parameters, works.**

It is clear that the project opens research and development perspective:

This is the use of tactile force sensors for achieving an apparatus to carry out clinical trials for analysis of plantar pressures distribution under static and dynamic function.

In this case it is possible to use a larger number of sensors (to increase the accuracy of information on foot position) and the software development so that, comparing the gait evaluation data of patients with those of healthy subjects, to be able to detect some pressure schemes / energy consumption / etc., which are characteristic to patients who have static and dynamic posture disorders.

#### REFERENCES:

- [1]. Pontzer H. *A new model predicting locomotor cost from limb length via force production.* J.Exp.Biology, 2005, 208:1513-1524 .
- [2]. Donelan JM, Kram R, Kuo AD. *Simultaneous, positive and negative external mechanical work in human walking.* J.Biomechanics , 2002, 35:117-124.
- [3]. Griffin TM, Roberts TJ, Kram R. *Metabolic cost of generating muscular force in human walking:insights from load-carrying and speed experiments.*J.Appl.Physiol, 2003, 95:172-183.
- [4]. Browning RC, Kram R. *Energetic cost and preferred speed of walking in obese vs. normal weight women.* J.Obesity Research, 2005, vol.13, No5:891-899.
- [5]. Minetti AE, Saibene F. *Mechanical work rate minimization and freely chosen stride frequency of human walking: a mathematical model.* J Exp.Biol.170, 1992, 19-34.
- [6]. Auvinet B, Bilekot R, Alix AS, Chaleil D, Barrey E. *Gait disorders in patients with fibromyalgia.* J.Joint Bone Spine 73 , 2006, 543-546
- [7]. [Fawcett T. *An introduction to ROC analysis.* J.Pattern Recognition Letters 27, 2006, 861-874.