STATISTIC PROCESSING OF MEASUREMENTS DONE WITH CALORCRO EQUIPMENT FOR ASSESSING THE GAIT ENERGETIC EXPENDITURE AT HEALTHY SUBJECTS AND PATIENTS SUFFERING FROM OSTEOARTHRITIS OF LOWER LIMBS

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Abstarct. *Based on the endeavour of using movement as an efficient treatment, the CALORCRO project has as an aim to promote physical effort as a part of osteoarthritis treatment in Romanian clinics. The project partners worked out both a method to evaluate the gait energetic expenditure and a portable computerized equipment to measure the gait parameters. The newness of both method and equipment consists in the concept of merging the advantages of the two existing systems: pedometer and treadmill with embedded force platforms, in order to evaluate the gait energetic expenditure. The objective of this study was to find the altering degree of some gait kinematic parameters and of the gait energetic expenditure (total expended power) of the subjects suffering from osteoarthritis of the lower limbs compared to healthy subjects, using the CALORCRO device.*

1. MATERIALS AND METHODS

1.1. Sample.

We studied 8 healthy women with the following characteristics: mean age 44.67±13 years, mean body weight 74.47±11 kg, mean lower limb length 94.85±4.2 cm and also a second group of 9 patients with osteoarthritis (ankle – 2 patients, knee – 4 patients, hip – 3 patients), who have the following characteristics: mean age 67.11±7.82 years, mean body weight 82.73±17.05 kg, mean lower limb length 82.67±3.27 cm. The healthy subjects were selected from persons who never suffered from diseases that affect the locomotion system.

1.2. Equipment and procedure.

Each subject performed three trials of 20 m normal gait on a horizontal surface and was equipped with the portable device CALORCRO, consisting of two overshoe supports carrying force sensors, two signal conditioning blocs, a data acquisition, processing and displaying system. The gait energetic expenditure calculation algorythm is based on the assessment of the internal and external work, using as input data the vertical ground reaction forces (VGRF) of each foot, the coordinates of the force sensors in the sensor supports and anthropometric data of the subject. The algorythm was verified through com-paring our results with those existing in other similar works [1], [2], [3] and also by simultanously testing several healthy subjects equipped both with our device and with the portable device Cosmed K4b^2, (indirect calorimetry). The validation of the measured values of the healthy subjects’ VGRF and their graphical display in time was achieved by comparing these with those given by the PEDAR-NOVEL equipment. In order to accomplish this the CALORCRO software comprises o function that aquires data files *.fgt* of the PEDAR-NOVEL equipment. The working procedure of the CALORCRO device consists of instruc-ting the subject, mounting equipment, recording the gait trial, printing the Gait Analysis Report (GAR).

1.3. Studied variables

1) Gait speed (V) (m/s) as ratio of walked distance and its duration,
2) Step length (cm) as ratio of walked distance and number of recorded steps;
3) Time parameters of gait: stride duration (s), stance phase duration (s) balance phase duration (s);
4) VGRF (N) as a sum of the forces measured by each sensor with a 100 Hz sampling frequency;
5) Vertical speed (VS) of the body Center of Mass (COM) as time integral of the VGRF divided by body mass;
6) Vertical displacement of COM as a time integral of VS;
7) External vertical power (EVP) (W) as a ratio of the total positive work of VGRF of both feet during a step and step duration [2], [3];
8) External power of forwardly oriented movement (EFP) (W) as a ratio of total positive work of the projection of the GRF in the gait direction of both feet during a step and step duration.
9) Internal power (IP) (W) evaluated with Minetti’s relationship [5];
10) R1 [W/(kg.m/s)] – ratio of the EVP (W) and body weight (BW)xV;
11) R2 [W/(kg.m/s)]– ratio of total expended power (EVP+EFP+IP) and (BWxV).

1.4. Statistics

For each healthy subject and each patient, mean values and standard deviations were computed for several parameters: gait speed, step length, stride duration,

duration of left stance relative to step duration, duration of right stance relative to step duration, *R1* – ratio of the EVP (W) and (BWx V), *R2* – ratio of total expended power and (BWxV).

In order to establish which of the variables (shown at 2.3) can discriminate a healthy subject from a sick one, sensitivity (Se) and specificity (Sp) of these variables were evaluated for both the group of healthy people and the group of the patients. Sensitivity is the probability of calling an actually sick person as sick, and specificity is defined as the probability of calling an actually healthy person as healthy. We tried to analyze the relevance of our test using the ROC method (Receiver Operating Characteristic). The ROC curve is a graphical plot of the sensitivity vs. (1- specificity), for the binary system of healthy and sick people. The two coordinates have a maximum value equal to 1. The shape of the curve itself depends on the threshold of that test. The classifier's best accuracy occurs at a threshold greater than 0.54. In order to get a quick interpretation of the ROC curve one uses the value of the area under the curve (AUC). This single scalar value represents the expected performance. Since the AUC is a portion of the area of the unit square, its value will always be between 0 and 1.0. However, because random guessing produces the diagonal line between (0, 0) and (1, 1), which has an area of 0.5, no realistic classifier should have an AUC less than 0.5. The AUC has an important statistical property: the AUC of a classifier is equivalent to the probability that the classifier will rank a randomly chosen sick person higher than a randomly chosen healthy person.

The data registered during the tests performed by the two groups of subjects (sick and healthy people)were worked out and shown in the tables I and II. ROC curves for each of the variables were plotted: walking speed (m/s), step length (m), step frequency (Hz), single support phase duration for each foot (left foot and right foot) relative to the step duration (%), rate between the vertical external power and the product: subject's weight x advance speed - *R1* (W/(kg.m/s)), the rate the total external power and the product: subject's weight x advance speed – *R2* (W/(kg.m/s)), (fig.1, fig. 2 and fig. 3).

Table I: Gait variables for healthy subjects (mean values)

Healthy subjects	Speed (m/s)	Step length (cm)	Stride frequency (Hz)	Right foot stance (%)	Left foot stance (%)	R1 W/(Kg.m/s)	R2 W/(Kg.m/s)
I	1,460	73,500	1,145	58,820	57,137	0,417	2,063
II	1,133	61,070	0,994	60,050	56,093	0,738	1,914
III	1,043	59,385	0,984	60,065	55,633	0,679	1,612
IV	1,257	54,323	1,146	58,483	57,937	0,551	1,711
V	1,280	63,000	1,080	57,893	53,240	0,822	1,963
VI	1,200	63,676	0,878	58,231	55,404	0,685	1,797
VII	1,400	68,858	0,849	58,118	54,630	0,461	1,824
VIII	1,670	75,716	1,140	57,524	53,778	0,350	2,026

Table II: Gait variables for patients (mean values)

Patients	Speed (m/s)	Step length (cm)	Stride frequency (Hz)	Right foot stance (%)	Left foot stance (%)	*R1* W/(Kg.m/s)	*R2* W/(Kg.m/s)
I	1,063	62,557	0,851	60,284	55,507	1,271	2,298
II	0,794	55,114	0,712	57,756	58,201	1,278	~
III	0,328	26,480	0,612	69,184	64,572	4,200	~
IV	0,854	53,363	0,830	62,646	59,836	1,414	~
V	0,362	34,060	0,554	64,800	64,344	3,384	~
VI	0,683	44,125	0,786	61,565	59,685	0,766	1,483
VII	0,821	50,673	0,829	64,226	61,420	0,732	1,569
VIII	0,848	52,918	0,808	61,473	61,949	1,532	2,382
IX	0,677	51,153	0,697	62,710	62,840	1,264	~

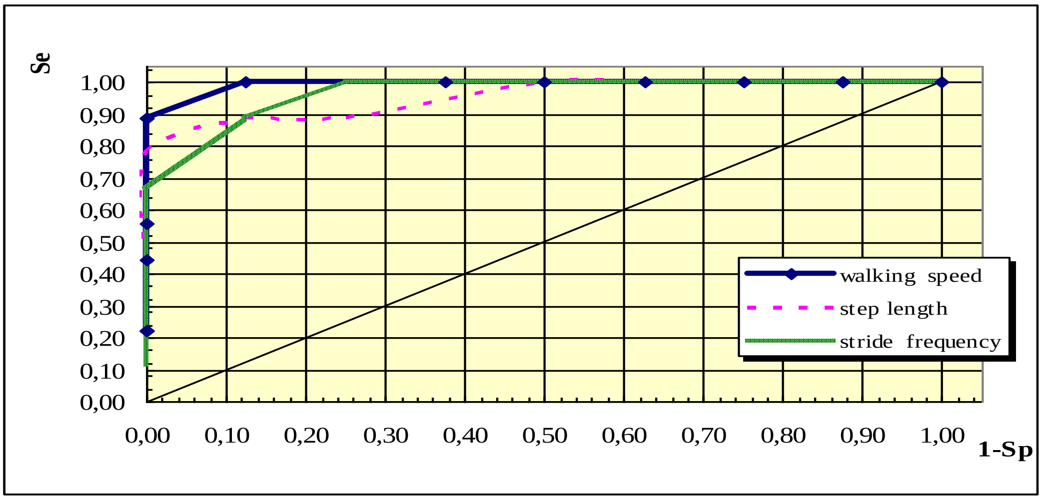

Fig. 1: ROC curves for: speed, step length, stride frequency. AUC for speed: 0,993; AUC for step length: 0,951; AUC for stride frequency:

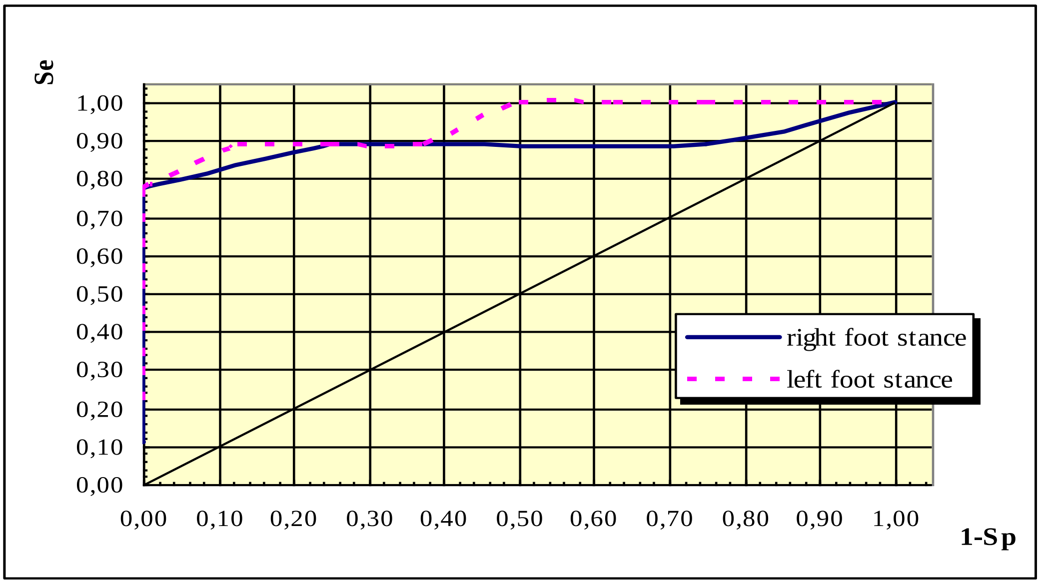

Fig. 2: ROC curves for duration of right/left foot stance relative to step duration. AUC for right stance: 0,883; AUC for left stance: 0,994

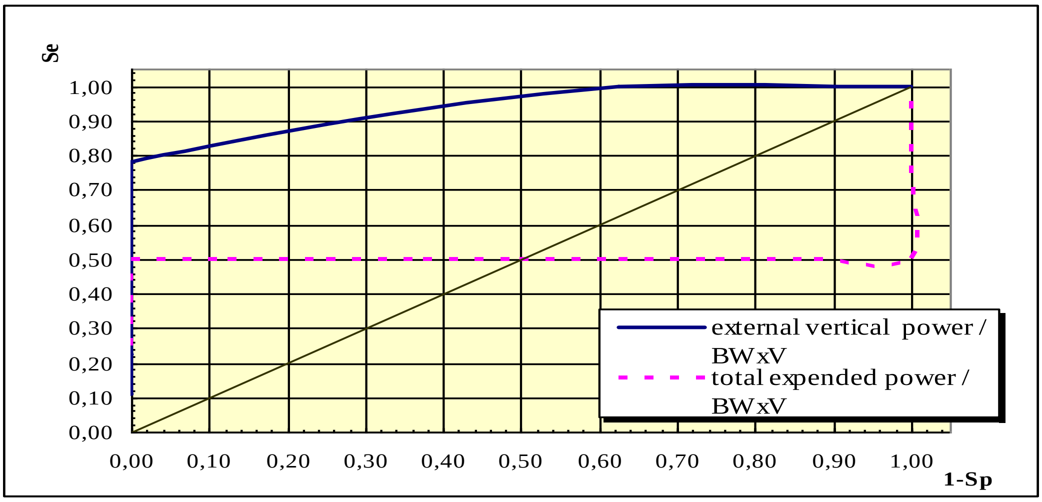

Fig. 3: ROC curves for *R1* and *R2*. AUC for *R1*: 0,937; AUC for *R2*: 0,500

Most of the curves plotted are characterized by an AUC greater than 0.880 so that one can assume that the analysis of the following variables: walking speed (m/s), step length (m), step frequency (Hz), single support phase duration for each foot (left foot and right foot) relative to the step duration (%), rate between the vertical external power and the product: subject’s weight x advance speed (W/(kg.m/s)), allow a good identification of the subjects suffering from osteoarthritis. The parameter represented by the total external power and the product of the subject’s weight and advance speed (W/(kg.m/s)) resulted in an AUC of only 0.5 and does not lead to a proper threshold that is able to positively allow an osteoarthritis diagnosis.

2. RESULTS

Gait Analysis Report (GAR) was printed of each gait trial (fig.4). The gait variables as mean values and their standard deviations were assessed for patients and healthy subjects; based on ROC curves, under ROC curve areas (AUC) and cutoff values were also assesssed (table III). The external power of the forwardly oriented movement (EFP) couldn’t be assessed for all the patients, as the VGRF curve had a shape showing no heel strike and no toe off action due to their disease. This impeded us to assess the EFP using EFP algorythm.

3. DISCUSSION

3.1. Equipment and procedure

The CALORCRO equipment and the assessing method used by us have several advantages in gait analysis of ambulatory patients suffering from osteoarthritis at lower limbs. The overshoe sensor supports do not disturb normal gait, measurements are quickly and noninvasively achieved and results include both main kinematic gait variables and the energetic expenditure. The assessing method allows the numerical evaluation of gait disturbances in clinical practice.

3.2 Gait disturbances of patients suffering from osteoarthritis of lower limbs

Analysis of the data recordings, graphs in GAR (fig.4) and statistical analysis of the studied variables brought about the following results:

- Patients in the initial disease stage, with painful decompensation have a shorter stance phase on the ill limb. If the functional decompensation prevailed the pain, the stance phases on both limbs are almost equal with those of healthy subjects.
- Patients in an advanced phase of disease show a much longer stance phase on both feet, compared to the healthy subjects.
- Depending on how severe the illness is, the patients’ VGRF curve shapes differ from the ones of healthy subjects, due to many irregularities, such as no heel strike and no toe off parts.The maximum force corresponding to the ill limb stance is smaller compared to the one of the healthy limb, as patients avoid pressing the ill joint.
- The vertical COM speed (VS) has an irregular variation.
- The mean values of the total expended power of the healthy subjects are similar with those found by other researchers [4].
- The patients’gait parameters differ from those of the healthy subjects in the following aspects: slower gait speed, shorter step length, smaller stride frequency, longer stance duration and greater values of R1 – ratio of EVP/(BWxV). The decrease of gait speed, step length, stride frequency shows that the patients suffering from lower limb osteoarthritis tend to slow down the limb movement, behaviour similar to the bradykinesia specific to the patients suffering from fibromyalgia [6]. This is accompanied by an increase of the stance duration and a decrease of the balance period, relative to the step duration. The alteration of the EVP consumed during the gait process proved to be another significant criterion in diagnosing patients with lower limbs osteoarthritis (table III).
- The statistical analysis of R2, that is the ratio of total expended power and (BWxV) showed that this parameter cannot discriminate the patients from the healthy subjects for the following reasons:
  - Patients suffering from an incipient lower limb osteoarthritis, who build a correct shape of the VGRF curve while walking, tend to combine an increase of the EVP with a decrease of both EFP and IP because they slow down the gait speed and decrease the stride frequency.
  - Patients suffering from lower limb osteoarthritis in an advanced stage of evolution show an increase of the EVP accompanied by a decrease of the IP, due to the diminution of the stride frequency. The abnormal shape of the VGRF curve while walking hindered us to apply the algorythm for assessing the EFP of these patients.
- The discrimination accuracy between the patients’ group and the healthy group is measured by the area (AUC) under the ROC curves (table III). The gait speed test and the stride frequency test make an excelent separation of the osteoarthritis patients and the step length working out this as well. The test R1– ratio of EVP/(BWxV) is a good test, but the test R2 – ratio of (EVP+EFP+IP)/(BWxV) is completely irrelevant, according to this analysis.

4. CONCLUSIONS

The gait parameters that differentiate patients suffering from lower limb osteoarthritis and healthy subjects were showed by the ROC analysis (table III). Those who generate an AUC value greater than 0.8-0.9, are the following: gait speed, stride frequency, step length, ratio *R1* of the EVP and (BWx V), stance relative to step duration.

Total expended power is not a relevant parameter as the human body has the natural tendency to conserve it's whole energy. As the total expended power is a sum of three power parameters (EVP, EFP, IP) the increase of one parameter (EVP) is accompanied by the decrease of the remaining, in order to conserve the body energy.

This study confirms that both kinematic and energy analysis are useful in evaluating both lower limb osteoarthritis stage of evolution and monitoring the treatment effects.

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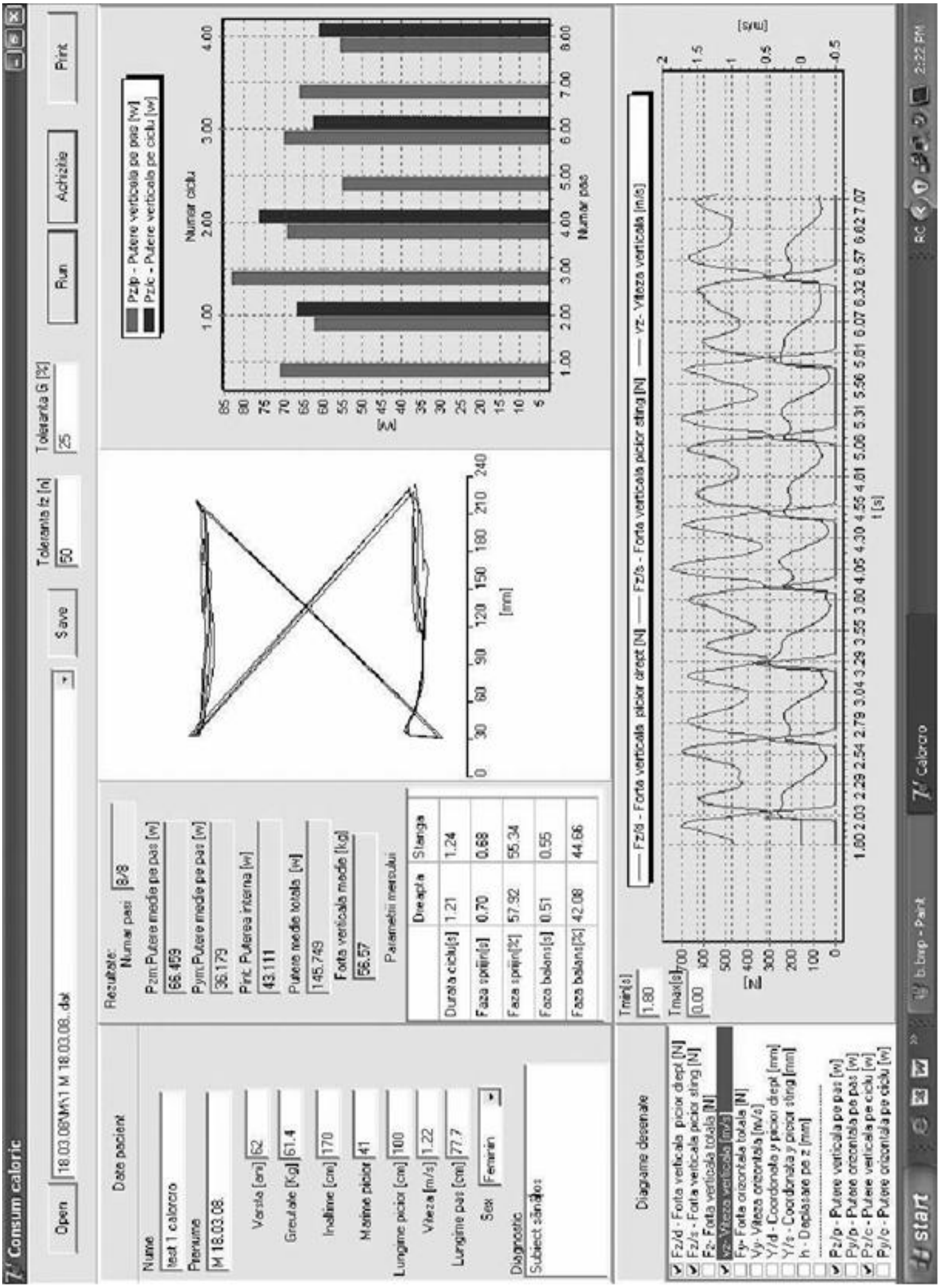
Table III: Statistical analysis of the gait parameterts of patients suffering from lower limb osteoarthritis and healthy subjects

Gait parameter	Subjects		Sensitivity and specificity of gait parameters		
	Patients	Healthy subjects	AUC	Discrimination	Cutoff
Walking speed (m/s)	0.714±0.224	1.305±0.187	0.993	excellent	0.999
Stride frequency (Hz)	0.742±0.099	1.027±0.066	0,965	excellent	0.938
Step length (cm)	47.82±10.56	64.94±6.78	0,951	excellent	53.55
R1 – ratio of external vertical power/ (BWx V) [W/(kg.m/s)]	1.76±1.132	0.588±0.157	0,937	good	0.928
R2 – ratio of total expended power / (BWxV) [W/kg.m/s]	1.933±0.409 (4 patients)	1.864±0.146	0,500	fail	-
Duration of left foot stance relative to step duration (%)	60.928±2.77	55.48±1.493	0.944	excellent	58.33
Duration of right foot stance relative to step duration (%)	62.73±3.016	58.648±0.89	0,889	excellent	60.43



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Toleranta fz [n] 50

Toleranta G [%] 25

Nume: test 1 calorcro

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Varsta [ani] 62

Greutate [Kg] 61.4

Inaltime [cm] 170

Marime picior 41

Lungime picior [cm] 100

Viteza [m/s] 1.22

Lungime pas [cm] 77.7

Sex: Feminin

Diagnostic: Subiect sănătos

Numar pasi 8/8

Pzm:Putere medie pe pas [w] 66.459

Pym:Putere medie pe pas [w] 36.179

Pint: Puterea interna [w] 43.111

Putere medie totala [w] 145.749

Forta verticala medie [kg] 56.57

	Dreapta	Stanga
Durata ciclu[s]	1.21	1.24
Faza sprijin[s]	0.70	0.68
Faza sprijin[%]	57.92	55.34
Faza balans[s]	0.51	0.55
Faza balans[%]	42.08	44.66

Tmin[s] 1.80

Tmax[s] 0.00

- ☑ Fz/d - Forta verticala picior drept [N]
- ☑ Fz/s - Forta verticala picior sting [N]
- ☐ Fz- Forta verticala totala [N]
- ☑ vz- Viteza verticala [m/s]
- ☐ Fy- Forta orizontala totala [N]
- ☐ Vy- Viteza orizontala [m/s]
- ☐ Y/d - Coordonata y picior drept [mm]
- ☐ Y/s - Coordonata y picior sting [mm]
- ☐ h - Deplasare pe z [mm]
- ☐
- ☑ Pz/p - Putere verticala pe pas [w]
- ☐ Py/p - Putere orizontala pe pas [w]
- ☑ Pz/c - Putere verticala pe ciclu [w]
- ☐ Py/c - Putere orizontala pe ciclu [w]

Fig. 4. Gait Analysis Raport (GAR) for a healthy subject