STUDY OF THE INFLUENCE OF ORTHOSES ON THE STABILITY OF HUMAN WALKING WITH OSTEOARTHRITIC KNEE

DANIELA TARNITA , MARIUS GEORGESCU, IONUT GEONEA

Abstract. In this paper, the tools of nonlinear dynamic analysis are used to quantify the influence of an orthosis on the human gait stability of a sample of patients suffering of osteoarthritic knee (OAK). The Lyapunov exponents (LEs) are computed based on the experimental data series collected during walking on horizontal treadmill (TM) for the movements in sagittal plane and frontal plane for all six main joints (hips, knees and ankles) of both lower limbs, in two cases: without orthosis and after two months of knee rehabilitation by using orthosis mounted on OAK. The results are compared with the similar values of LEs computed for a sample of healthy subjects. The result show the influence of the orthosis on the knee stability, but on the other joints' stability, is a significant one.

Key words: nonlinear dynamic, human gait, Lyapunov exponents, treadmill, osteoarthritic knee, orthosis.

1. INTRODUCTION

Among the elderly population, falls tend to occur from several factors that interact with each other [1]. These can be intrinsic (or biological) factors, such as a neurological mechanism, a chronic condition (such as Parkinson's disease), osteoarthritis, stroke, or extrinsic (or environmental) factors such as a slippery floor, various obstacles or slopes, poor lighting [2, 3]. Estimates show that globally, one in three people over the age of 65 falls at least once a year [4, 5].

The stability of an individual can be affected by musculoskeletal disorders. These are the most common causes of chronic pain and restrictions on mobility and physical performance, leading to an increase in morbidity [6]. Hundreds of millions of people suffer from such diseases globally, and this number is expected to increase with the aging of the global population [4, 6]. Many such diseases have the effect of losing stability. The instability causes falls which cause fractures or

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other traumas that require surgery and unavailability thus generating a significant economic and social impact [7–11].

One of the conditions that affects stability is arthritis. Of the over 100 types of arthritis, osteoarthritis (OA) is the most common form, affecting 32.5 million adults in the U.S. alone [12]. Joint osteoarthritis involves a degenerative process of cartilage in the joints that leads to their loss [6]. In the last stage of the disease, a joint replacement is usually required. Total hip replacement (THR) and total knee replacement (TKR) are treatments that can reduce pain and increase mobility, thus improving quality of life. It is estimated that the incidence rate of TKR will increase in Germany by approximately 43% between 2018 and 2050, [13] while in the U.S.A. the number of TKR is estimated to increase by 673% between 2005 and 2030 [14].

Problems of gait variability and stability of patients suffering from osteoarthritis and other aspects regarding the influence of knee osteoarthritis on the risk of falling have been studied in the literature [6, 15–20].

The use of a rehabilitation device, such as an orthosis or exoskeleton, is an alternative non-surgical and non-pharmacological solution for the treatment of osteoarthritis, a solution that improves gait parameters and stability of movement. These medical devices are often used as rehabilitation devices, and in the last decade, research related to their use and the effects they have on the rehabilitation of human gait is increasing both for orthotic systems [21–24] and for exoskeletal system [25–27] and robotic systems [28–31]. In the recent decade, the tools of nonlinear dynamic analysis and the Lyapunov exponents (LE) have been used by researchers in order to quantify the local dynamic stability of human walking [32–40].

In this paper, we use the tools of nonlinear dynamic analysis to quantify the influence of an orthotic device on the gait stability of a sample of osteoarthritic patients during walking on treadmill (TM), by using LEs computed based on the experimental data series collected for the lower limbs joints in sagittal plane and frontal plane.

2. EXPERIMENTAL STUDIES OF GAIT STABILITY

The equipment used in this research for data acquisition and processing is the Biometrics system [41, 42], which is based on wearable sensors such as electrogoniometers, very often used in research in the field of biomechanics, due to the advantages offered by them [16, 25, 28, 36, 43, 44]. The experimental data acquisition process is performed in real time. Electroniometers mounted on the subject's joints, Fig. 1, transmit the collected data to the portable DataLog unit, and the received signal is transmitted via Bluetooth to the PC. The DataLog unit, Fig. 1c allows the acquisition of both analog and digital data, on a maximum of 24 channels simultaneously, with frequencies up to 20,000 Hz.

a) b) c)

Fig. 1 – a) Biometrics equipment used to collect data during the treadmill test; b) electrogoniometers; c) DataLog device.

The data received by the computer is represented as diagram by Biometrics DataLOG software. Examples of diagrams represented in Biometrics based on acquired data for flexion-extension angles and rotation angles, measured in [deg] function of time [s] for the three joints of the right lower limb of a healthy subject are shown in Fig. 2.

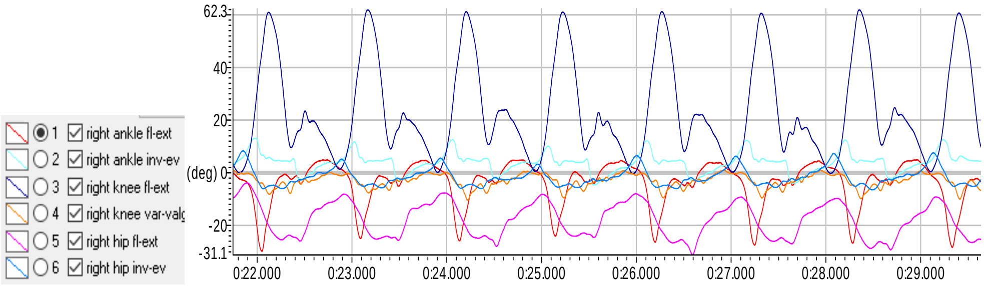

Fig. 2 – Real-time graphical representation (in the user interface of the Biometrics software) of consecutive cycles of angular amplitudes [deg] of the joints of the right lower limb, function of time [s].

In the bimechanical assessments of gait stability, an orthotic device designed and patented by our team is used (Patent no. RO132075 / 30.09.2019) [45], in order to improve gait and increase the stability of people with osteoarthritis of the knee, Fig. 3. The virtual model of the orthotic device is shown in Fig. 3a, and the phisical prototype mounted on the patient's osteoarthritic knee is shown in Fig. 3b. The varus correction system stabilizes the knee by eliminating or minimizing the abnormal lateral movements (in the frontal plane) that occur in gonarthrosis, while allowing flexion-extension movements. The connection between the upper frame (1) and the lower frame (2) is made on the side of the knee by coupling, using hinge-type couplings (3) and (4), with the upper bar (5) and the lower bar (6), connected, in turn, by two chain links and a central piece in the shape of a spool (7) [45]. The screws provided in the hinge-type systems act and allow the component (3) to be pushed towards the medial, thus correcting the pathological varus and stabilizing the knee joint.

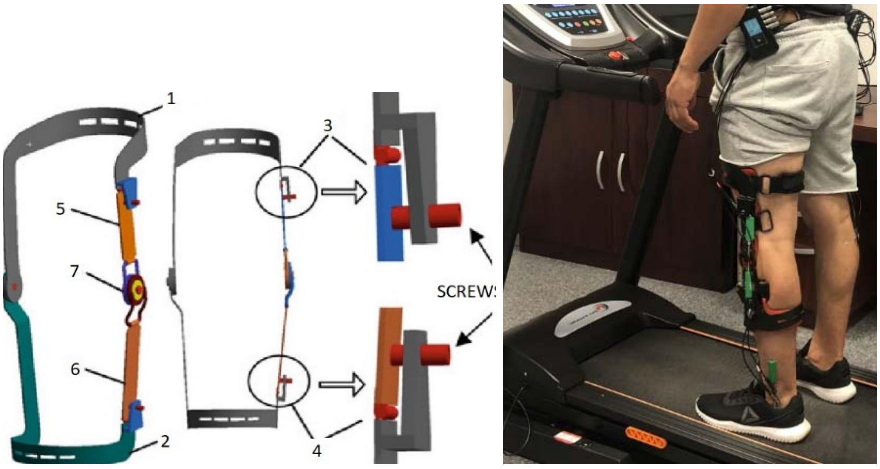

Fig. 3 – a) Virtual model of the proposed orthotic device: 1 – upper frame; 2 – lower frame; 3 – upper hinge; 4 – lower hinge; 5 – upper stem; 6 – lower rod; 7 – correction system; d) the physical prototype of the orthosis mounted on the patient.

The experimental study involved a sample of 8 healthy subjects (HS) and a sample of 5 patients suffering of osteoarthritic knee (OAK). The medium values and standard deviations of the main anthropometric data of both samples are presented in Table 1.

Table 1

Anthropometric data (mean and standard deviation) for HS and OAK patients

	Data	Age [years]	Weight [kg]	Height [cm]
HS	Mean (st.dev)	32.4 (3.45)	67.3 (4.22)	172.6 (3.29)
OAK patients	Mean (st.dev)	61.6 (2.78)	76.3 (3.17)	165.3 (3.43)

The HS sample performed a test on horizontal treadmill at a speed of 5 km/h, while the OAK patients performed the same test, but in two different cases: first test – before using the orthosis and the second test – two months later, after its use for knee rehabilitation.

A total number of 108 time series were collected from both samples: 48 time series = 8 HS × 6 joints, respectivelly, 60 time series = 5 patients × 6 joints × 2 tests (with and without orthotic device mounted on OAK).

3. NONLINEAR ANALYSIS

The results of the nonlinear analysis consist of quantifying the influence on the dynamic stability of human gait of the orthotic device mounted on the knee affected by osteoarthritis, for a sample of patients. As indicators of stability, the maximum Lyapunov exponents were calculated for the experimental data series collected using the Biometrics acquisition system during the horizontal treadmill tests.

3.1. STATE SPACE RECONSTRUCTION

The reconstruction of the state space is the central piece of the nonlinear analysis of time series. The procedure involves a series of time, Fig. 4 with experimental measurements of a dynamic system quantity.

In a state space reconstructed in m dimensions, with a time delay d, a point at time t is a vector xt with the following components:

$$X_t = \left(S_t, S_{t+d}, S_{t+2d}, \ldots, S_{t+(m-1)d}\right),\ t = 1, \ldots, n \quad (1)$$

Reconstructed space vectors are also called "Takens vectors" [46]. In order to be able to apply the "Time Delay Method" [47] it is necessary to choose in advance the appropriate parameters for the reconstruction. These are the time delay and the dimension of the reconstruction.

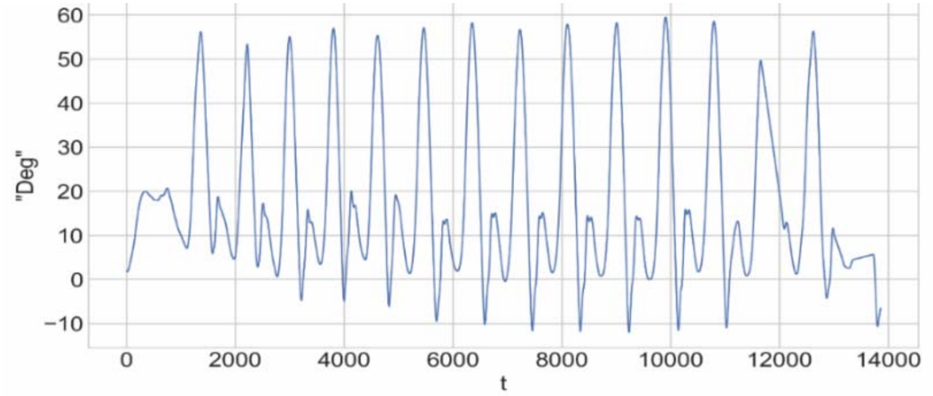

Fig. 1 – Time series of the angle of flexion-extension movement of the right knee joint for walking on TM, subject 1.

The determination of the time delay is done by selecting the first minimum of the average mutual information function (AMI) [48]. Considering two random variables, *X* and *Y*, then their mutual information, *I(X;Y),* is defined as:

$$I(X;Y)=\sum_{i}\sum_{j}p\left(x_{i}y_{j}\right)\log_{2}\frac{p\left(x_{i}y_{j}\right)}{p\left(x_{i}\right)p\left(y_{j}\right)}, \tag{2}$$

where $p\left(x_{i}y_{j}\right)$ is the distribution function of the common probability between *X* and *Y*; $p\left(x_{i}\right)$ and $p\left(y_{j}\right)$ are the distribution functions of marginal probability of *X* and *Y*.

In the context of using real arithmetic on an infinite amount of data and without noise, the reconstruction theorems only require that the delay *d* be greater than zero and that it is not a multiple of one of the periods of the orbit [46, 49–51].

Figure 5 shows the graph of the average mutual information function of the time series of the angles of flexion-extension movement of the right knee joint of subject 1 for normal gait. The first minimum value occurs at *d* = 360. The graphical representations of the AMI function was obtained for every time series in Python [52] using the Pytisean library [53], which in turn uses the Tisean package [54].

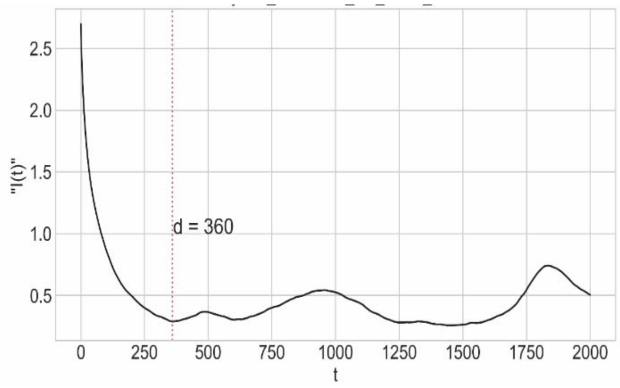

Fig. 5 – Average mutual information for time series of angles of flexion-extension movement of the right knee joint.

The reconstruction dimension is calculated using the false nearest neighbours (FNN) method, introduced by Kennel [55], and is chosen as that size for which the proportion of close false nearest neighbors is below 10%. The method involves the unfolding of intercalated orbits (resulted from the projection of an attractor of a dynamic system into a smaller dimensional space), so that there are no more intersections of trajectories. Figure 6 shows a graphical representation of the percentage of false neighbors calculated for the time series of the angles of flexion-extension movement of the right knee joint of subject 1 for normal gait. The value of the reconstruction dimension can be estimated as *m* = 4. Similar graphs were obtained for the rest of the time series with measurements of the joints of the samples of subjects and patients.

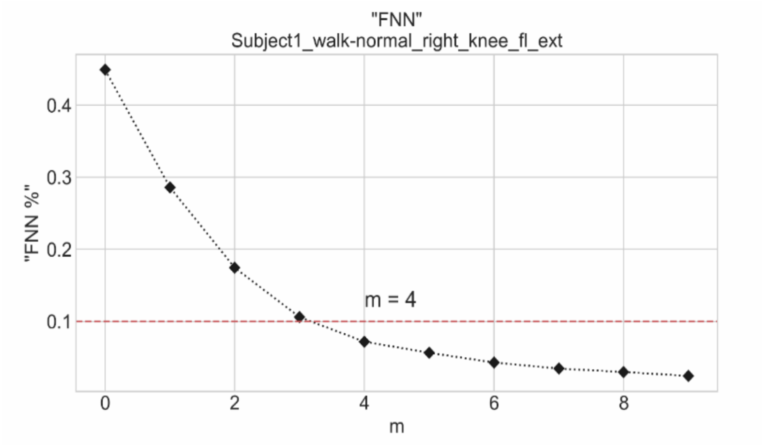

Fig. 6 – Graphical representation of the percentage of false neighbors for the human knee joint of subject 1 – walking plane treadmill, calculated by the FNN method.

Using the two parameters, the state space is reconstructed. In Fig. 7 are plotted the first three dimensions of the reconstructed state space starting from the time series of the flexion-extension angle of the right knee joint of subject 1 for the test of walking on TM at a speed of 5 km/h.

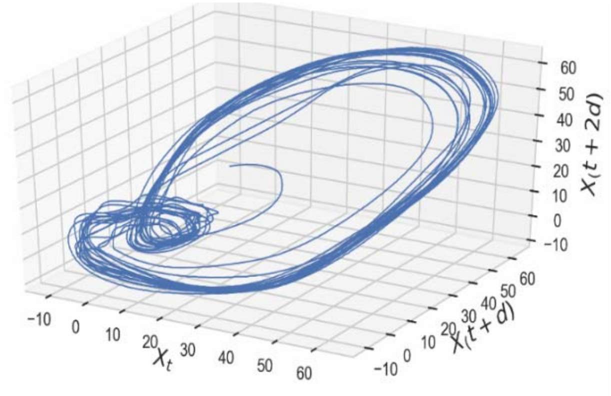

Fig. 7 – The reconstructed state space corresponding to the time series of the angle of the flexion-extension movement of the right knee joint for normal walking.

3.2. LYAPUNOV EXPONENTS

Lyapunov exponents provide a direct measure of the sensitive dependence to the initial conditions by quantifying the exponential rates at which neighboring orbits diverge (converge) to an attractor as the system evolves over time [56–59]. A d-dimensional system will have d Lyapunov exponents, $(\lambda_1, \lambda_2, ..., \lambda_d)$, each representing the rate of increase or decrease of small perturbations along each major axis in the state space of that system. If $\delta(0)=\delta_o$ is a small initial perturbation in the system from the initial condition, the space state vector is done by the relation:

$$x_n = x_0 + \delta_0 \, . \tag{3}$$

For a value of δ_o appropriately chosen, the exponential rate of expansion, which means stability, or of contraction, which means instability, defines the LEs as being:

$$\lambda_i = \lim_{t\to\infty} \frac{1}{t} \ln\left(\frac{\|\delta(t)\|}{\|\delta_0\|} \right), \tag{4}$$

where ||.|| represents the vector norm operator [39].

If the system has at least one positive Lyapunov exponent and is purely deterministic, then it is "chaotic". In the three-dimensional state space ($d = 3$) defined for a continuous dissipative system, different combinations of positive, negative and zero exponents determine the type of dynamics underlying the system [60]. The "lyap_k" procedure of the Tisean package can be used to estimate the largest Lyapunov exponent of a given time series using the Rosenstein-Kantz algorithm [61]. The values of the maximum Lyapunov exponents resulting for all time series were positive, which shows that the angular movements of the human joints have a deterministic component that has chaotic characteristics. Table 2 shows the mean LE values for frontal and sagittal movements of the joints of the patient samples (with and without mounted orthotic device) and subjects, and in Figs. 8, 9 and 10 these values are represented graphically, for a suggestive illustration.

Table 2

Mean values of the maximum Lyapunov exponents for all joints for subjects and patients (with and without orthotics) for the plane treadmill walking test

Sample	Joint	Angle	Left leg (OAK)	Right leg
Patients without an orthosis	ankle	fl-ext	0.448	0.397
		inv-ev	0.470	0.525
	knee	fl-ext	0.601	0.489
		var-valg	0.494	0.451
	hip	abd-add	0.505	0.393
		fl-ext	0.417	0.370
Patients with orthosis	ankle	fl-ext	0.406	0.396
		inv-ev	0.377	0.363
	knee	fl-ext	0.498	0.473
		var-valg	0.394	0.358
	hip	abd-add	0.375	0.365
		fl-ext	0.356	0.338

Healthy subjects	ankle	fl-ext	0.391	0.387
		inv-ev	0.364	0.356
	knee	fl-ext	0.425	0.429
		var-valg	0.388	0.375
	hip	abd-add	0.361	0.363
		fl-ext	0.354	0.335

The mean values of the maximum Lyapunov exponents obtained for the measurements of the healthy subjects varied from 0.349 to 0.429 while those for the sample of patients without orthosis varied between 0.370 and 0.601, and with orthosis between 0.335 and 0.498. Compared to the values obtained for the joints of healthy subjects, the values obtained for patients are higher both for the joints of the healthy leg and for the joints of the leg affected by osteoarthritis. The most significant differences were those at the knee joint (Fig. 8) for which the mean values obtained by HS for the flexion-extension movement are 0.425 in the left knee and 0.429 in the right knee, while patients without an orthotic device obtained a value of 0.601 in the affected knee and 0.489 in the right knee. The patients with mounted orthotics obtained an average of 0.498 in the osteoarthritic knee and 0.473 in the knee of itshealthy limb.

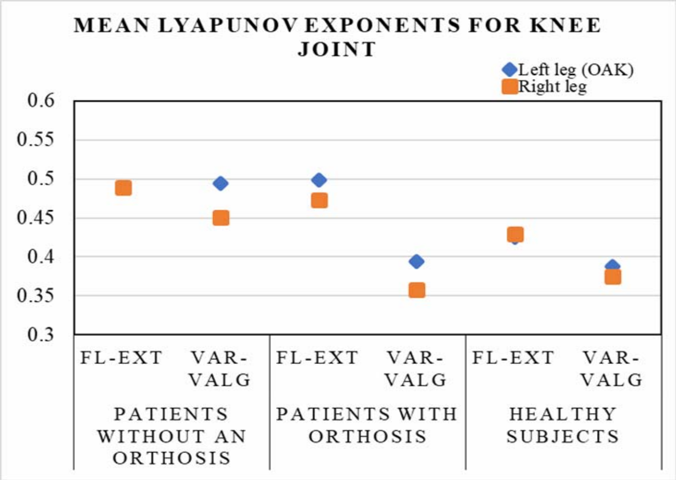

Fig. 8 – Graphical representation of the average values of the maximum LEs obtained for the knee joint.

Higher mean values of LEs corresponding to the patients' knees reflect more divergence, decreased local stability in knee movement, while lower values computed for healthy subjects reflect less divergence, and more stability.

The influence of the orthosis on the stability of the osteoarthritic knee movement and on the gait stability is a positive one, the average values of the maximum Lyapunov exponents being lower than those obtained for the osteoarthritic knee without orthosis but also closer to the values obtained for the patients' normal knees and those obtained for the healthy subjects. The results confirm that the influence of an orthotic device mounted on the osteoarthritic knee on its stability is significant.

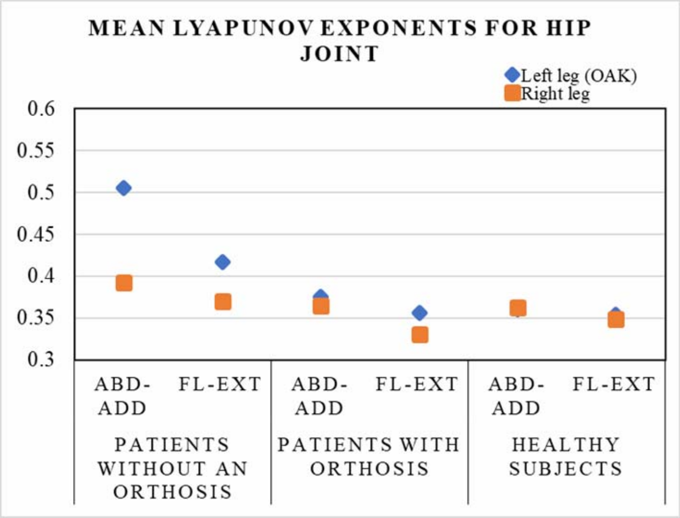

Fig. 9 – Graphical representation of the average values of the maximum LEs obtained for hip joints.

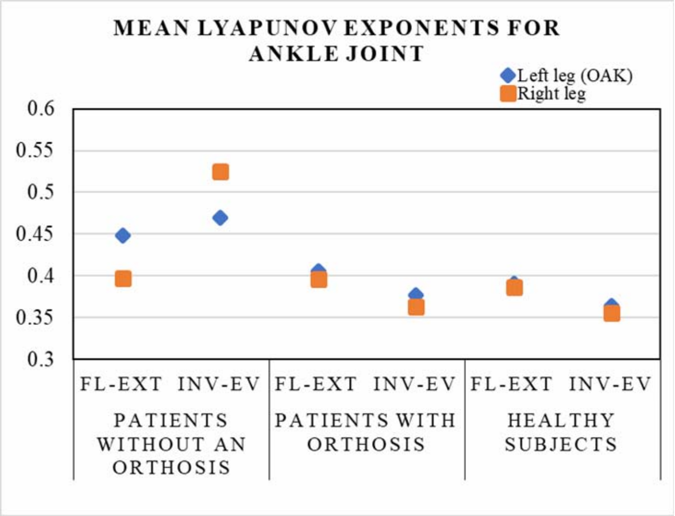

Fig. 10 – Graphical representation of the average values of the maximum LEs obtained for ankle joints.

So, the movement of the affected knees presents a more unstable dynamic comparing with the movement of healthy knees of the same patient. This decrease in local stability can be caused by pain or instabilities determined by various injuries.

4. CONCLUSIONS

In this paper the influence of an orthosis on the stability of the osteoarthritic knee, as well as on the stability of the other main joins of both lower limbs of a sample of patients suffering of OAK is studied. The kinematic data series of the flexion-extension angles in sagittal plane and of rotation angles in frontal plane for a sample of healthy subjects and for a sample of patients were analysed in order to obtain new information about the sensitivity of the locomotor system to local perturbation. A study based on the tools of nonlinear dynamics to visualize the steady state kinematics of human joints movements of lower limbs is presented and showed that there was a chaotic feature of angle movements, using the chaotic measure, such as LEs. The LEs computed for each joint during the walking test on horizontal treadmill were positive values.

Larger values of LEs obtained for affected knees, as well as the hips and ankles of the affected lower limbs suggest a higher instability and increased sensitivity, while smaller values reflect a local stability. The influence of the orthotic device on the movement rehabilitation and on the movement stability is a positive one and it is reflected by the decreasing of the Les for the affected knees, but, also, for the other main joints of the lower limbs.

The results obtained can be used as a reference for normal joint movements, as well as for further studies of abnormal movements and early detection of instability and avoidance of the risk of falling, extremely dangerous for the associated serious consequences.

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