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# Study of human ankle joint stability during stairs up and stairs down

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**Abstract.** In this paper, nonlinear dynamics tools are the basis for analyzing the stability of the human ankle joint during stairs up and stairs down. Lyapunov exponents are determined in order to quantify the human ankle stability from biomechanical experimental data collected for flexion-extension angle and inversion-eversion angle of right and left ankles in 9 healthy subjects and 7 patients with knee osteoarthritis. Both samples performed the experimental stair ascending and descending tests. To analyze the acquired biomechanical time series, the Rosenstein-Kantz algorithm and TISEAN software are used.

**Keywords:** human ankle, stairs up, stairs down, knee osteoarthritis, stability, Lyapunov exponents.

## 1. Introduction

Human movements analysis, including gait analysis, is more and more studied in the last years, being very useful for the design and optimization of the orthotic devices and exoskeletons [1-4], or bio-inspired medical robots [5-6]. The ankles have an important role in walking, running, jumping, as well as in the movement stability and the human body integrity, taking into account the shocks that can cause instability and the risk of fall and fracture will be increased. About 45-65% of the people who suffer an ankle sprain will gradually get the chronicity of the ankle instability [7].

Wearable sensors, more used in biomechanical data collection, present the advantage that they allow monitoring subjects and patients, acquiring data in their environment and their daily activities [8-10], identifying kinematic differences

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between healthy subjects (HS) and patients [1-3], or monitoring the rehabilitation of human joints movements [5,6,11].
Ascending and descending the stairs are daily activities that require increased effort, with particular emphasis on people with musculoskeletal conditions, such as, for example, osteoarthritis of the joints. [11-17].
OAK is met in proportion of about 50 percent at the persons over 65 years. In Fig.1 it can be seen the human knee joint (anterior view) in an advanced stage of osteoarthritis. The cartilage surface could be fissured, leading to pain, swelling and loss of joints mobility.

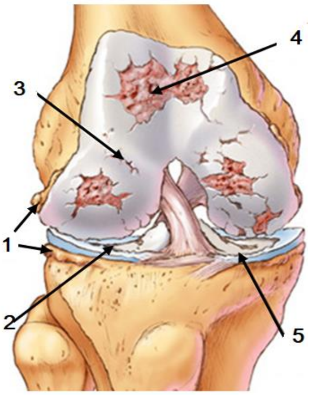



Fig. 1. Human knee joint affected of osteoarthritis in advanced stage [18]:
1) Bone formations; 2) Highly eroded lateral meniscus; 3) Eroded femoral cartilage - incipient state; 4) The area of femoral cartilage totally affected; 5) Medial meniscus eroded in advanced state.

Osteoarthritis of the knee is found more often in women, primary arthrosis constituting 70%, while in men the secondary arthrosis is more often present (53%) [19]. Osteoarthritis is the fourth cause of health problems in women and eighth in men. More than 80% of osteoarthritic people has limited mobility, while more than 25% of these people cannot perform important activities of daily life. Osteoarthritis is frequently associated with obesity (between 45-65%) and varicose veins (between 20 and 44% of cases). By limiting physical activity due to pain and reduced joint mobility, this condition causes depression, anxiety, absenteeism from work and impairment of daily life [19].
The new mathematical tools of nonlinear dynamics are more and more used in the last period for characterizing and quantifying the stability and the variability of the human walking and to allow analysing the stress in human joints [20-24]. An important parameter used to quantify the local dynamic stability is Lyapunov exponent (LE).
In this paper, the stability of human ankle joint for HS and patients suffering of knee osteoarthritis (KOA) is quantified by using tools of nonlinear dynamics, as LEs, during ascending and descending the stairs. The influence of the KOA on the

ankle stability is analyzed and the results obtained by the patients are compared with the results obtained by the HS.

## 2. Experimental study

The experimental measurements of the ankle angles (flexion-extension in sagittal plane and inversion-eversion in frontal plane) are performed by using the Biometrics data acquisition system [25], based on electrogoniometers - wearable sensors used in biomechanics and clinical medicine [1, 3, 5, 6, 14, 20-23, 26-28]. The biomechanical data were collected from the two ankles of each participant in experiment with the help of electrogoniometers, connected with 8-channel DataLOG device. The acquisition frequency was 500 Hz. Schema-block of experimental data collection is shown in Fig. 2.
The Biometrics system is based on different types of flexible electrogoniometers used for synchronized 3D gait measurement. The electrogoniometers have two separate connectors, each of them being used to measure the angle variation in both orthogonal planes. In Fig. 3 subjects with Biometrics system mounted on them is shown.

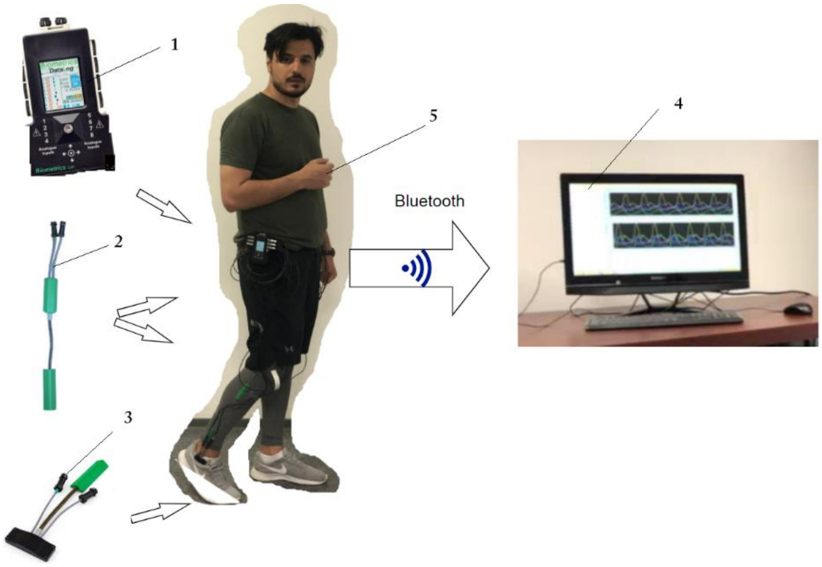



Fig. 2. Schema block of data collection: 1 - DataLog device; 2 - electrogoniometer SG150; 3 - electrogoniometer SG110e; 4 - diagrams displayed on screen; 5 - subject.

Fig. 3. The equipment mounted on a subject during ascending and descending the stairs.

In fig. 4 movements of ankle joint are presented.

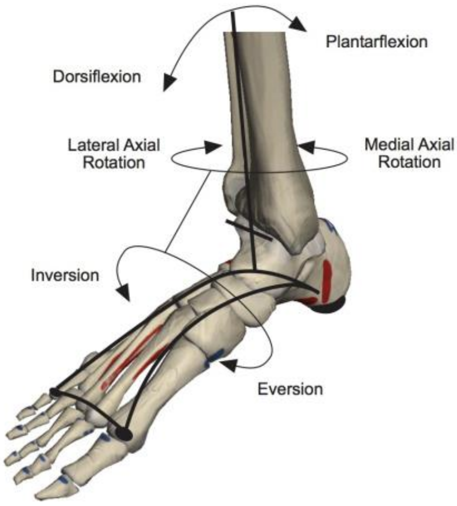



Fig. 4. Movements of the ankle joint [29].

Two samples, one composed of 9 HS and one composed of 7 patients suffering by KOA, second stage, performed the two experimental tests. The average anthropometric data of HS and patients are shown in Table 1. The subjects do not have any kind of pain or any problem related to locomotion. The present study was approved by the Ethical Committee of the University of Craiova.

Table 1. Average **a**nthropometric data of participants' samples.

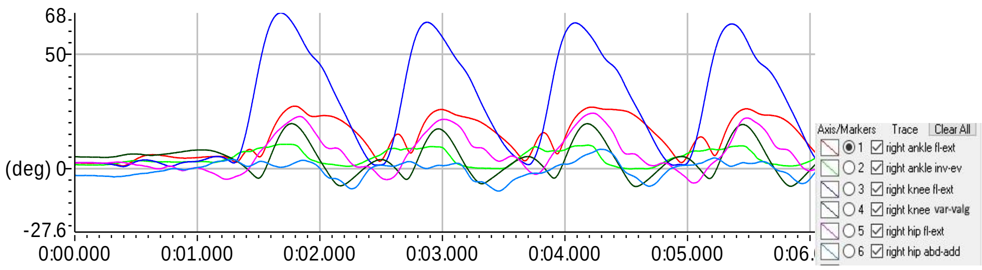
| | Age [years] | Weight [kg] | Height [cm] | Lower limb length [cm] |
|---|---|---|---|---|
| Subjects - Average (StdDev) | 29.45 (1.67) | 73.78 (5.83) | 178.32 (7.59) | 81.57 (8.21) |
| Patients - Average (StdDev) | 65.73 (2.98) | 69.45 (7.37) | 164.58 (8.29) | 78.27 (8.95) |

## 2.3. Experimental tests

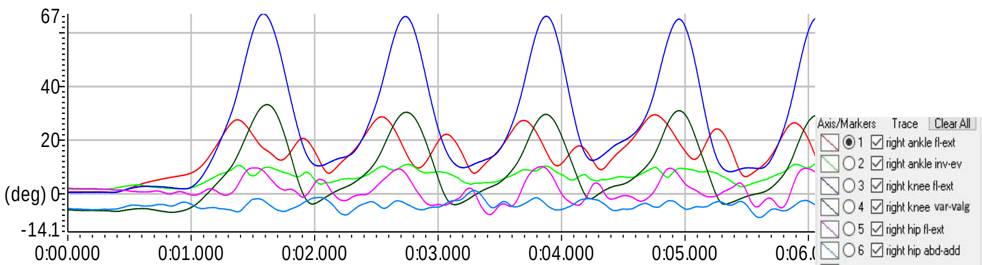
Both samples performed two experimental tests: stairs up and stairs down, on a staircase with 12 stairs, having the dimensions: height = 0.18 m, width = 0.3 m, length = 1.5 m.

## 3. Results

In Fig.5, consecutive cycles of flex-ext angles performed in sagittal plane and rotation angles performed in frontal plane, in respect with time [s], for the right lower limb of Subject 4 for both experimental tests, collected and computed by Biometrics software, are shown.




a)




b)

Fig. 5. Grapf of variation of experimental flexion-extension angles,
in sagittal plane, for right leg of Subject 4: a) stairs up; b) stairs down.

## 4. Dynamic analysis

The values of LEs, are computed starting from the experimental biomechanical time series acquired for both movements of the ankle: flexion-extension and inversion-eversion, for the ankles of HS, as well as for the patients suffering of KOA. The first step of the nonlinear analysis algorithm consists into the reconstruction of the state space S, by using the method of generation of the delay coordinates vectors [30]:

$$x_n = [s(t_0+nT_s); s(t_0+nT_s+d), .... s(t_0+nT_s+(m-1)d)] \qquad (1)$$

where $d_E$ is an integer named embedding dimension, the notation s(.) is a scalar function, $T_s$ is the sampling time, n = 1, 2,..., m, while $d = kT_s$ is the corresponding time delay. In [30-33] is shown that the dynamics of the original system and of the reconstructed state space are equivalent, both spaces having the same invariants, one of them being the LEs. In Fig. 6 the state-space reconstruction corresponding to ankle flexion–extension movement of Subject 4 and Patient 2 are presented. Similar diagrams are obtained for all participants in the experiment. For HS' ankle the cycle's curves show less variance in their trajectories, they are more compact, the amplitudes tend to be constant, while the curves traced for the ankle affected by the influence of the KOA show an increased divergence and spread in their trajectories.

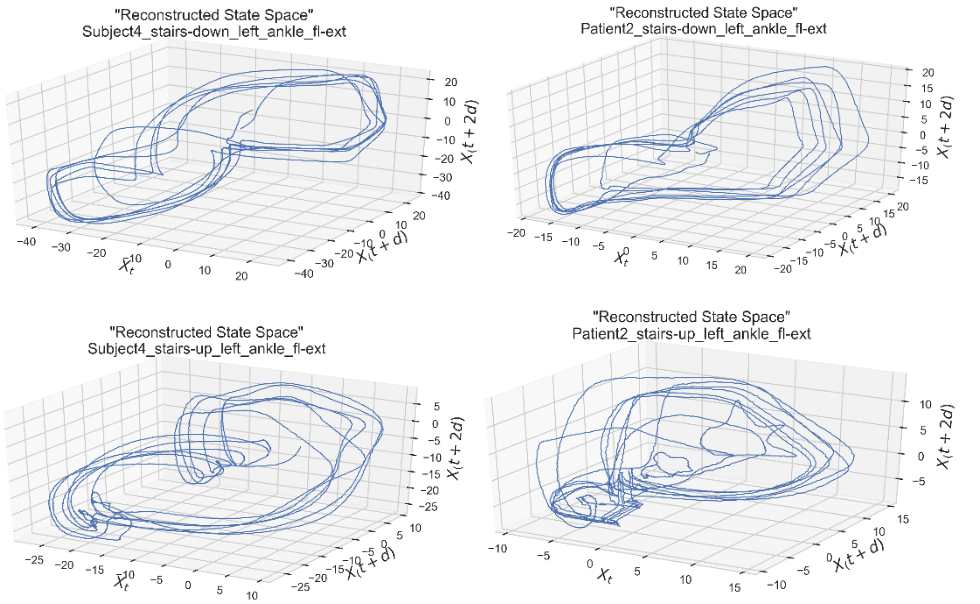



Fig. 6. State space reconstruction of flexion-extension of the right ankle of Subject 4 and of Patient 2.

The corresponding time delay, d, is determinate for all time series, using the average mutual information function (AMI) [34] and TISEAN software [35]. The

AMI function sets the value of d to be equal to the value of the delay appropriate to the first minimum of the function (Fig. 7).

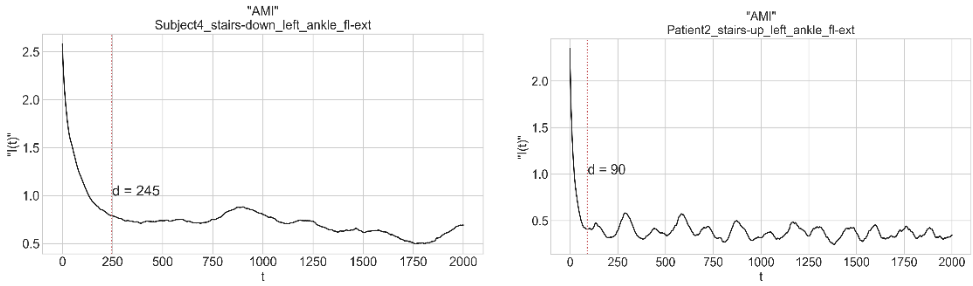



Fig. 7. AMI function diagram for stairs-down Subject 4 and Patient 2.

A suitable embedding dimension, m, was computed for each experimental time series, by using the False Nearest Neighbor method (FNN) [36] (Fig.8). The value of m is given by the minimum value for which the curves of the reconstructed state vector cannot overlap in state space.

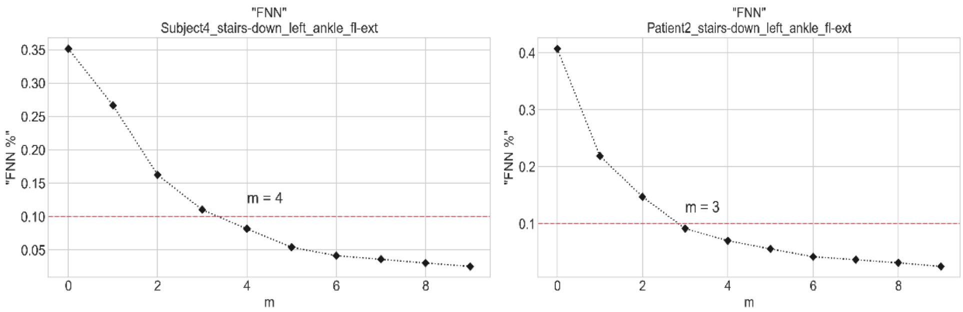



Fig. 8. FNN diagram for Subject 4 and Patient 2 - stairs down, left ankle, flexion-extension.

The LEs are computed in TISEAN package, based on the Rosenstein algorithm [37]. If LEs increase, then the local dynamic stability decreases [31-32]. The LEs calculated for all time series were positive, that is equivalent with the fact the ankle is a deterministic chaotic system, according to [32-34]. In Table 2 the average values of the LEs for both ankle movements of HS' sample and patients' sample are presented, while in Fig.9 these values are plotted.

Table 2. Average values of LEs for both ankles of HS and patients in stairs up and stairs down tests.

| | Test | Angle | Left Ankle | Right Ankle |
|---|---|---|---|---|
| **Subjects** | Stairs up | fl-ext | 0.5085 | 0.5437 |
| | | inv-ev | 0.4695 | 0.4161 |
| | Stairs down | fl-ext | 0.6714 | 0.7266 |
| | | inv-ev | 0.4845 | 0.4379 |
| **Patients** | Stairs up | fl-ext | 1.2727 | 0.9869 |
| | | inv-ev | 0.7507 | 0.5889 |
| | Stairs down | fl-ext | 0.8546 | 0.7715 |
| | | inv-ev | 0.7318 | 0.6048 |

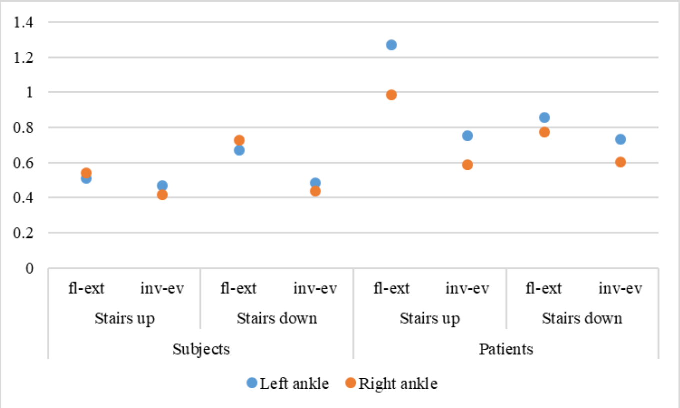



Fig. 9. Plots of average values of LEs computed for ankle during stairs up and stairs down, for HS and patients, flexion-extension and inversion-eversion movements.

The values obtained for all Les were positive values, that means the human ankle movements exhibit chaotic characteristics. For the ascent and descent tests, the mean values of the maximum LEs for the ankle joints obtained for the sample of HS ranged from 0.4379 to 0.7266, while for the sample of patients affected by osteoarthritis the mean values of the maximum LEs ranged from 0.5889 to 1.2727. Higher values of LEs calculated for patients are associated with more divergence and increased variability of joint movement, while lower values calculated for the HS for stairs up and stairs down show local stability, less variability, less sensitivity to disturbances and a big resistance to step-by-step variability. The observation is valuable for both HS and patients. We also observed higher values obtained by patients for both tests. For the ankle of osteoarthritic lower limb the values are higher than those obtained for the ankle of the other leg.

## 4. Discussions and conclusions

In the present study, the aim was to study the influence of the KOA on the stability of human ankle joints for the stairs up and stairs down activities. The values of LEs were calculated for both tests, for all subjects and patients. A comparison is made between the values of LEs computed for subjects and patients and for the samples. The Biometrics system is used for acquisition and processing the biomechanical data. The results can be used as a data base for future studies including both HS and patients, taking into account the importance and complexity of this human joint.

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