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NONLINEAR MOVEMENT OF HUMAN KNEE OVERGROUND & ON TREADMILL

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Abstract: *The objective of this study is to quantify and investigate nonlinear motion of the human knee joint for a sample of 5 healthy subjects over ground, on plane treadmill and inclined treadmill with an angle of 10^o, using nonlinear dynamics stability analysis. The largest Lyapunov exponents (LLE) are calculated as chaotic measures from the experimental time series of the flexion-extension angle of human knee joint.*

Keywords: *human knee, treadmill, nonlinear dynamics, Lyapunov exponents, phase plane, dominant frequency*

1. Introduction

Variability of gait can be defined as the variance of the gait parameter around the mean, and a broad range of variability measures has been reported in literature [1, 2, 3]. Many studies that investigated the human movements and variability were conducted using different speeds that were measured from over ground walking [4-9]. Motorized treadmills are widely used in research in biomechanical studies of human locomotion or in clinical therapy. The purpose of [10] was to characterize the differences between over ground and treadmill walking in terms of stride-to-stride variability. Biomechanics research in gait has focused largely on walking on the horizontal [9-12], with less attention for inclined surfaces [13-15].

During last years, a lot of new mathematical tools have been used to characterize the stability and the nonlinear features of gait variability. Local dynamic stability refers to the behaviour of a system in response to very small perturbations [16]. It is quantified by the maximum Lyapunov exponent which is a measure of the ability of the walking subject to maintain continuous motion and to attenuate the effects of the local perturbations [2, 5, 8, 10, 11, 16-19].

The objective of this study is to quantify and investigate nonlinear motion of the human knee joint on plane and inclined treadmill, using nonlinear dynamics stability analysis. The largest Lyapunov exponent (LLE) and correlation dimension will be calculated as chaotic measures from the experimental time series of the flexion-extension angle of human knee joint.

2. Nonlinear Dynamics

2.1. State Space Reconstruction

One method to reconstruct the state space S is to generate the so-called delay coordinates vectors [20].

The dynamics in the reconstructed state

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space is equivalent to the original dynamics, so an attractor in the reconstructed state space has the same invariants, such as Lyapunov exponents and correlation dimension [21].

2.2. Embedding Dimension

The embedding is a mapping from one dimensional space to a m-dimensional space and is based on the principle that all the variables of a dynamical system influence one another. In conformity with the theorem of Takens, a map exists between the original state space and a reconstructed state space and the dynamical properties of the system in the true state space are preserved under the embedding transformation, [22]. One of the most used method for measuring the minimal embedding dimension is introduced by Kennel et al. [23] and it is called the false nearest neighbour (FNN) method. To properly reconstruct the chaotic flow, a minimum dimensionality is needed and this is the value where the percentage of false nearest neighbour's approaches zero is chosen as d_E value [17, 24, 25].

2.3. Lyapunov Exponents

Lyapunov exponents (LLE) exhibit the rate of divergence or convergence of the nearby trajectories from each other in state space [26], providing a measure of the system sensitivity to its initial conditions. For a 3-dimensional state space there will be an exponent for each dimension: all negative exponents will indicate the presence of a fixed point; one zero and the other negative indicate a limit cycle; one positive indicates a chaotic attractor [17]. The value of the LLE is the main exponent that quantifies the exponential divergence of the neighbouring trajectories in the reconstructed state space and reflects the degree of chaos in the system, being necessary to identify the stability of the time series.

3. Experimental study

The experimental method which allows obtaining the kinematic parameters diagrams for the human knee joint uses a Biometrics data acquisition system based on electrogonimeters [25]. The block schema of the acquisition data system is presented in Fig. 1. In Fig. 2 the data acquisition system mounted on the subject is shown. Measurements were performed on a sample of 5 healthy subjects.

They were pain-free and had no evidence or known history of motor and skeletal disorders or record of surgery to the lower limbs. The experimental tests were approved by the University of Craiova human ethics research committee and they were performed in the biomechanics laboratory at INCESA Research Centre, University of Craiova. Before starting the experiments there were collected anthropometric data from healthy subjects.

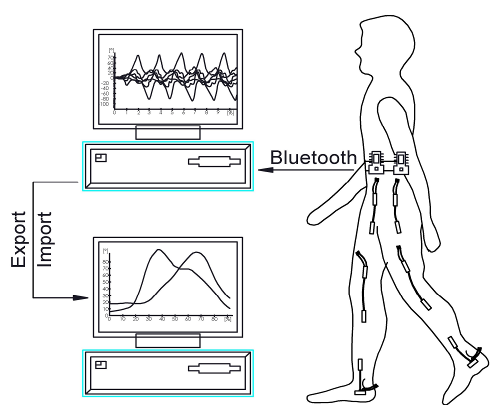

Fig. 1. *Block schema of the acquisition data system based on electro goniometer.*

Fig.2. *Subject with data acquisition system mounted*

In Table 1 the anthropometric data of healthy subjects are presented.

Table 1.

Subject	1	2	3	4	5
Age [years]	33	31	39	35	30
Weight [kg]	82	76	79	85	78
Height [cm]	173	180	179	178	175
Hip–knee length [cm]	43	50	53	42	46
Knee–ankle length [cm]	38	43	42	40	40

Table 1-*Anthropometric data of subjects*

4. Results

The angular amplitudes of human knee flexion-extension during the gait on the treadmill were obtained for each test as data files. In Figure 3 the diagram of the knee flexion-extension angles Φ_1 for Test 1, Φ_2 for Test 2 and Φ_3 for Test 3 [degrees] in respect with time [s] for subject 1 obtained by Biometrics system, are presented. In this study the human lower limb was considered as a nonlinear system that can achieve dynamic equilibrium.

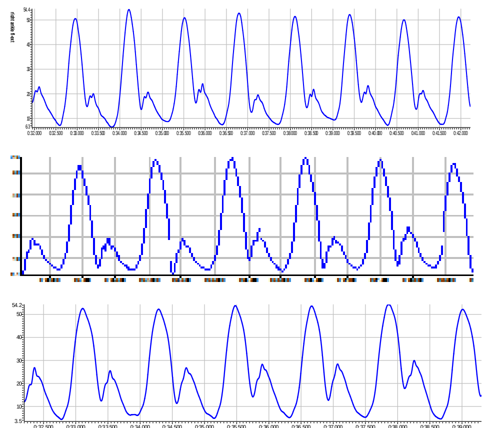

Fig. 3, *Diagram of the knee flexion-extension angles for Test 1, Test 2 and Test 3 [degrees] in respect with time [s] for subject 1*

For biomechanical gait analysis tests it is important to determine also the dominant frequency. Based on data calculated by Fast Fourier Transform (FFT), it was designated as the dominant, the movement frequency at which the highest value is registered (Fig. 4). Based on data calculated by FFT, it was designated as the dominant, the movement frequency at which the highest value is registered (Fig. 4).

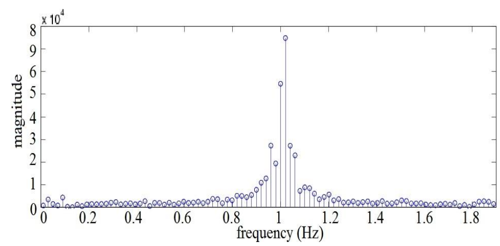

Fig. 4. *Graphical representation of dominant frequency of Subject 1 – plane treadmills*

For flexion-extension motion of the human knee of the 5 subjects, we determined the dominant frequency using FFT algorithm (Table 2.).

	Dominant Frequency (Hz)		
Subject	Over ground	Plane treadmill	Inclined treadmill
1	**1.056**	**0.921**	**0.918**
2	**1.032**	**0.912**	**0.91**
3	**1.097**	**1.016**	**0.997**
4	**1.031**	**0.987**	**0.978**
5	**1.096**	**0.954**	**0.943**

Table 2 – *Dominant frequencies of gait cycles, for all the three tests of 5 subjects*

It can be seen that the dominant frequency values are higher for all subjects in the over ground test, then drops to the second test on plane treadmill and are at the lowest level in the third test on inclined treadmill.

Phase plane portraits will be used to characterize the kinematics of the system when it attained this equilibrium. Using phase plane portraits one can correlate the joint rotations with the respective joint velocities. The phase plane plot is a two-dimensional plot in which the time derivative $\dot{\phi}$ is plotted versus ϕ at each data point. Phase plane portraits can be utilised to compare the joint kinematics for plane walking versus inclined walking. The phase plane plots, shown in Fig. 5, and Fig. 6 contain information as the graph of data for both tests for subject 3. For all other subjects, the phase plane plots are similar.

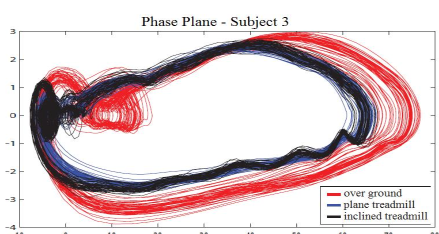

Fig. 5. *Graphical representation of phase-plane portrait of Subject 3 for all tests.*

The plots traced for plane treadmill show less divergence in their trajectories, while the trajectories obtained for inclined treadmill at 10° are confined within a tighter space. The phase plane curves are more compact for walking on plane treadmill than for walking on inclined treadmill.

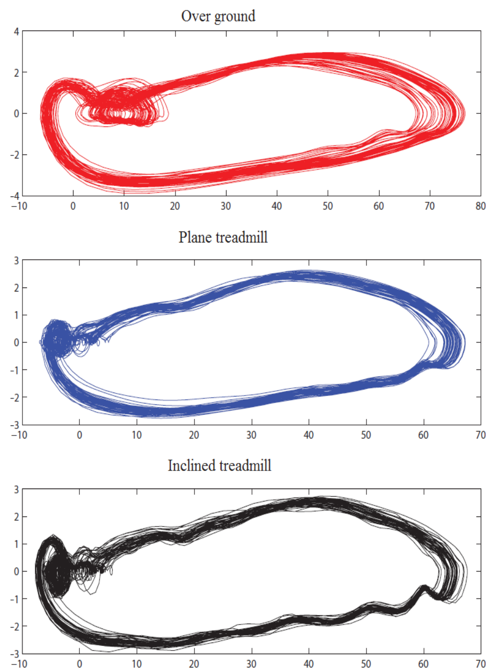

Fig. 6. *Graphical representation of phase-plane portrait of Subject 3*

Comparing the phase-plane graphics, it can be seen that on treadmill the amplitude of consecutive steps tends to be constant, while in the case of overground the amplitude varies. It can be seen that the phase planes are almost concentric curves, inside is the curve corresponding to plane and inclined treadmill and outside are the curves corresponding to overground.

Similar comparatives curves of phase plane portraits are obtained for all subjects.

Traditional measures of variability are insufficient to characterize the local dynamic stability properties of locomotor behaviour. Therefore, the experimental data is analysed using the LLE as a measure of the stability of a dynamical system. In fig. 7, the flow diagram of nonlinear dynamic analysis is shown.

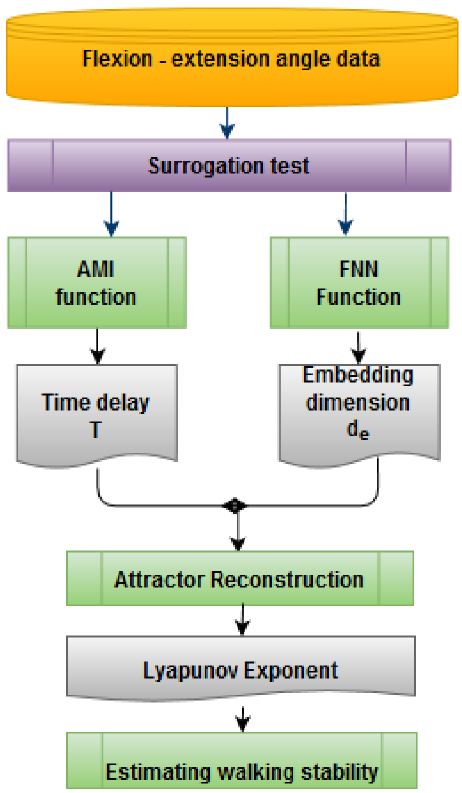

Fig. 7. *Flow diagram of the chaos analysis from the joint angle data.*

The time delays were calculated for each of the data files from the first minimum of the Average Mutual Information (AMI) function [17, 18]. The adopted value for time delay for subject 3 is equal to 16 seconds (Fig.8). The time Delay values used for state-space reconstruction in the case of plane treadmill are presented in table 3.

A suitable embedding dimension was chosen by using the false nearest neighbour (FNN) method [17,18]. Embedding dimension is the minimum value that trajectories of the reconstructed state vector may not cross over each other in state space. The results were similar for all-time series and indicated an appropriate embedding dimension of $d_E = 5$ (Fig.9).

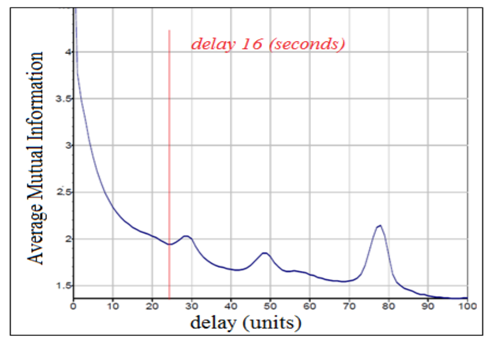

Fig. 8. *Graphical representation of AMI function of Subject 3 – plane treadmill*

	AMI – Optimal Delay		
Sub	Bins	Delay (units)	Delay (seconds)
1	**14**	**21**	**0.13**
2	**14**	**29**	**0.18**
3	**14**	**26**	**0.16**
4	**13**	**29**	**0.18**
5	**14**	**23**	**0.14**

Table 3 – *Time Delay used for state-space reconstruction (plane treadmill)*

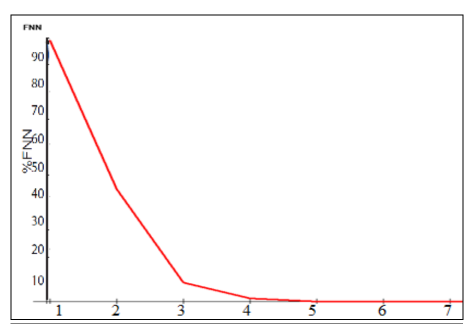

Fig. 9. *Graphical representation of false nearest neighbours' percentage for Subject 1- plane treadmill*

We calculated the LLE values for all-time series using special software to analyse nonlinear time series data, “TISEAN (TIme SEries ANalysis)” [19, 26, 27]. The value of the LLE is the main exponent that quantifies and reflects the degree of chaos in the system. If the system is known to be deterministic, a positive Lyapunov number can be taken as proof of a chaotic system. The LLE calculated for all-time series were positive, so we can conclude that the human lower limb is a deterministic chaotic system.

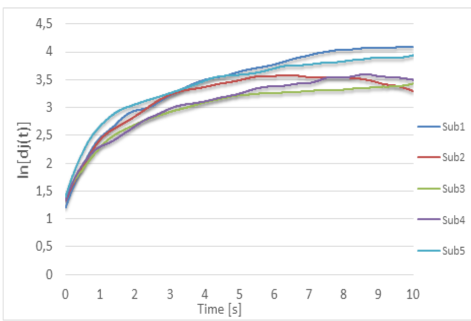

Fig.10- *Graphical representation of Long Lyapunov Exponents of all 5 subjects – plane treadmill*

In Table 4 the LLE values of the three tests of healthy subjects are presented. The existence of the positive Lyapunov exponents indicates that the time series of the movement amplitude has instability.

LLE	Sub 1	Sub 2	Sub 3	Sub 4	Sub 5
Over ground	**0.058**	**0.060**	**0.055**	**0.061**	**0.062**
Plane Treadmill	**0.052**	**0.056**	**0.054**	**0.058**	**0.055**
Inclined Treadmill	**0.062**	**0.064**	**0.059**	**0.063**	**0.058**

Table 4. *Long Lyapunov values obtained for all subjects for each test*

We can see that the LLE values are smaller on the plane treadmill (the range values is 0.052-0.058) than on the inclined treadmill (the range values is 0.058-0.064). One of the explanations could be that the effects of the inclined plane on the variability are more pronounced than in the situation of plane walking. Larger values of LLEs are associated with more divergence, a decrease of local stability and increase of knee flexion variability, more sensitivity to perturbations, while smaller values obtained for plane treadmill reflect a local stability, less divergence and variability, less sensitivity to perturbations.

The results are similar with those obtained by other researchers in their nonlinear dynamics studies applied at human joints movements [2, 18].

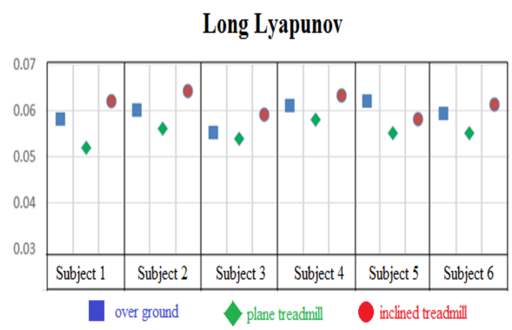

Fig.11 *Graphical representation of Long Lyapunov Exponents of all 5 subjects*

5. Conclusions

A study based on the tools of nonlinear dynamics to visualize the steady state kinematics of human knee movement is presented. The kinematic data of the flexion extension angles for three tests of human knee joint were analysed. The purpose of this study was to investigate the biomechanics of chaotic characteristics of movements of the knee joint. We applied the chaotic analysis to the rhythmic flexion-extension movements of human knee joint and showed that there existed the chaotic feature of angle positions using the chaotic measure such as the largest

Lyapunov exponent. The LLE obtained for each test of human knee joint were positive values which suggest that human knee motions show chaotic characteristics.

The results of this study can be used in the medical field to develop new artificial devices that could reproduce the motion of the lower limb, in robotics for humanoid robots which movements are inspired by human movement or as educational robot in order to study the complex process of locomotion [6, 15].

References

1. Hausdorff, J.M., Rios, D.A., Edelberg. H.K.: *Gait variability and fall risk in community-living older adults: a 1-year prospective study*. Archives of Physical Medicine and Rehabilitation, (2001) Vol. 82 (8), p. 1050ï 6.
2. Dingwell, J.B., Cusumano, J.P., Cavanagh, P.R., Sternad, D.: *Local dynamic stability versus kinematic variability of continuous overground and treadmill walking*. Journal of Biomechanical Engineering (2001), Vol. 123 (1), p. 27ï 32.
3. Hausdorff, J.M.: *Gait dynamics, fractals and falls: finding meaning in the stride to-stride fluctuations of human walking.* Human Movement Science (2007), Vol. 26 (4), p. 555ï 89.
4. Owings, T.M., Grabiner, M.D.: *Variability of step kinematics in young and older adults*. Gait & Posture (2004), Vol. 20 (1), p. 26-29.
5. Tarnita, D., Marghitu, D.: *Analysis of a hand arm system.* Robotics and Computer-Integrated Manufacturing (2013), Vol. 29 (6), p. 493ï 501.
6. Tarnita, D., Catana, M., Tarnita, D.N.: *Experimental measurement of flexion-extension movement in normal and osteoarthritic human knee.* Romanian Journal of Morphology and embryology (2013), Vol. 54 (2), p. 309ï 313.
7. Winter, D. A. : *Biomechanical Motor Patterns in Normal Walking*. Journal of Motor Behavior (1983), Vol. 15 (4), p. 302-330.
8. Dingwell, J.B. et. al.: *Kinematic variability and local dynamic stability of upper body motions when walking at different speeds*. J Biomech (2006), Vol. 39 (3), p. 444-52.
9. Jordan, K., Challis, J.H. et al.: *Walking speed influences on gait cycle variability.* Gait Posture doi:10.1016/j.gaitpost.2006.08.010.
10. Terrier, Ph., Dériaz, O.: *Kinematic variability, fractal dynamics and local dynamic stability of treadmill walking*. Journal of NeuroEngineering and Rehabilitation (2011), Vol. 8, p. 1-13.
11. Tarnita D., Catana, M., Tarnita, D.N.: *Nonlinear Analysis of Normal Human Gait for Different Activities with Application to Bipedal Locomotion*. Ro. J. Tech. Sci. Appl. Mech. (2013) Vol. 58, Nº 1-2, p. 177ï 192.
12. Kawamura, K., Tokuhiro, A., Takechi, H.: *Gait analysis of slope walking: a study of step length, stride width, time factors and deviation in the centre of pressure.* Acta Medica Okayama (1991), Vol. 45 (3), p. 179ï 184.
13. Leroux, A., Fung, J., et. al.: *Postural adaptation to walking on inclined surfaces: I.* Normal strategies. Gait & Posture (2002), Vol. 15 (1), p. 64ï 74.
14. Sun, J., Walters, M., Svensson, N., Lloyd, D.: *The influence of surface slope on human gait characteristics: a study of urban pedestrians walking on an inclined surface*. Ergonomics, (1996), Vol. 39 (4), p. 677ï 692.
15. Tarnita, D., Georgescu, M., Tarnita, D.N.: *Application of Nonlinear dynamics to Human Knee Movement on Plane and Inclined Treadmill, in New Trends in Medical and Service Robots*. Human Centered Analysis, Control and Design, Springer Publishing House,

ISBN 978-3-319-30673-5, (2016), Vol. 39, p. 59-73.
16. Hyun, G.K.: *Kinematic and Motor Variability and Stability during Gait: Effects of Age*. Walking Speed and Segment Height, Doctoral Thesis, The University of Texas, Dec. 2007.
17. Dingwell, J.B., Cusumano, J.P.: *Nonlinear time series analysis of normal and pathological human walking*. Chaos (2000), Vol. 10, p. 848-863.
18. Abarbanel, H.D.:*Analysis of Observed Chaotic Data*, Spinger-Verlag New York, Inc. (1996).
19. Rosenstein, M.T., Collins, J.J., DeLuca, C.J., *A practical method for calculating largest Lyapunov exponents from small data sets.* Physica D: Nonlinear Phenomena (1993), Vol. 65, p.117ï 134.
20. Packard, N.H., et al.: *Geometry from a Time Series*. Physical Review Letters (1980), Vol. 45, p. 712-716.
21. Nayfeh, A.H.: *Introduction to Perturbation Techniques*. Wiley-Interscience, NY, (1981).
22. Takens, F., *Detecting Strange Attractors in Turbulence*. Lecture Notes in Mathematics, ed. D.A. Rand & L.S. Young (1981), Vol. 898, p. 366-381.
23. Kennel, M.B., Brown, R., et. al.: *Determining Embedding Dimension for Phase Space Reconstruction Using a Geometrical Construction*. Physical Review A (1992), Vol. 45, p. 3403-3411.
24. Boccaletti, S., Valladares, et al.: *Reconstructing Embedding Spaces of Coupled Dynamical Systems from Multivariate Data*. Physical Review E (2002), Vol. 65, 035204(R) 1-4.
25. Tarnita, D.: *Wearable sensors used for human gait analysis*, Rom J Morphol Embryol 2016, Vol. 57 (2), p. 373-382.
26. Schreiber T, Schmitz: *A. Surrogate time series. Physica D-Nonlinear Phenomena (*2000), 142:346ï 82.
27. Hegger R, Kantz H, Schreiber T.: *Practical implementation of nonlinear time series methods: the tisean package. Chaos* (1999), 9:413ï 35