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Experimental evaluation of the treadmill speed and incline effects on the ankle kinematics in healthy subjects

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Abstract. This paper presents the results obtained in the experimental evaluation of flexion–extension angles of the ankle joints during 10 tests of walking on horizontal and inclined treadmill. The tests were performed at two different speeds, 5 km/h and 10 km/h, and five different incline angles: 0, 3, 7, 11 and 15 degrees by a sample of 11 healthy subjects. The medium cycles are determined and plotted for all subjects and for the sample, for all experimental tests. The medium cycle was calculated for each test, for each subject, and for the entire sample. A comparison is made between the average cycles of each test obtained for the sample. Increasing the TM inclination leads to an increase in the maximum value of the flex-ext angle. The influence of increasing the TM inclination angle on the variation of the flex-ext angle is stronger than that of increasing the walking speed.

Keywords: horizontal and inclined treadmill, human ankle, treadmill tests, medium cycle.

1. Introduction

Nowadays, the importance of gait measurement and analysis has encountered and appreciated in biomechanics and clinical research. The kinematic parameters of gait give useful information for diagnosis and restorative action [1].
Various tools for collecting information on different gait parameters help the successful use of gait analysis techniques [2], allowing an objective assessment and providing a large volume of information about the gait of monitored subjects [2]. The considerable interest in the development of human gait evaluation technologies used outside the laboratory, allowing measurements at home, at the workplace, at

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the hospital, in gyms, has led to the development and use of systems based on portable sensors. They make it possible to monitor subjects and patients affected by movement disabilities, obtaining data acquired in the patient's natural environment, as well as during the person's daily activities. In the medical field, knowing the characteristics of walking, monitoring and evaluating changes in human walking, reveals important information about the objective quantitative measurement of walking parameters and about the evolution and early diagnosis of various diseases [2-7]. Wearable sensors systems include sensors such as electrogoniometers, accelerometers, gyro sensors, force sensors, electromyographic sensors, etc. The systems have been used to determine some spatiotemporal parameters, such as the number of steps, step length, cadence and walking speed [7, 8].

The advantages and validity of wearable sensors to collect a variety of gait parameters are presented in different studies on healthy subjects or pathological subjects [3, 8-12], to identify kinematic differences between osteoarthritic patients and healthy subjects [13-16].

Previous studies of walking kinematics analyzed the influence of walking speed variation on walking variability both on the ground and on horizontal and inclined treadmills (TM) [17– 20]. Human gait analysis is very useful for the design of rehabilitation devices, such as orthotic systems or exoskeletons [13, 18, 21-23] or bio-inspired robotic structures, such as medical robots [24, 25].

Ankle joints are complex anatomical structures. They have a particularly important role in walking, running, jumping, regarding the kinematics, dynamics, but also the stability of the movement and the integrity of the human body, considering the shocks it endures and which can cause instability or even sprains and fractures, if they are not carefully protected. A percent of about 40-70% of individuals who suffer an initial ankle sprain will develop chronic ankle instability [16], and the risks of fall and fracture is increased.

The aim of this study consists into the measurement of the flexion-extension angle (flex-ext) of the ankles of both human lower limbs during 10 tests of walking on horizontal and inclined TM performed by a sample of 11 healthy subjects. The medium walking cycles were obtained for each experimental test and an analyze of the influences of speed and incline is done.

2. Materials and methods

2.1. Data acquisition systems

Biometrics system [4] is a biomechanical data acquisition and process system based on wearable sensors such as electrogoniometers, accelerometers, force platforms, myometers, dynamometers and many other types of sensors. Data LOG MWX8 acquisition unit (Fig. 1) is a wearable device, which can be attached to the human body, allowing the simultaneous data collection from a maximum 24 sensors with frequencies varying from 100 to 20 000 Hz. Real-time data transfer is carried out, allowing the possibility of storing data in the device by using a memory card [4]. The Biometrics system is provided with a set of light and flexible electrogoniometers recommended and used for precise and synchronized 3D gait measurement, in the sagittal and frontal planes [4]. Flexible electrogoniometers (Fig. 1.) have two separate connectors, each measuring an angle variation in each of the two perpendicular planes, sagittal and frontal. Collection of experimental data stages, in accordance with schema-block in Fig.1 are the following:

- Collection of biomechanical data, as data files, by using electrogoniometers
- Transmission of data files to DataLOG devices,
- Real-time data transmission to the computer via Bluetooth®
- Converting data into angle diagrams for all joints and displaying them.

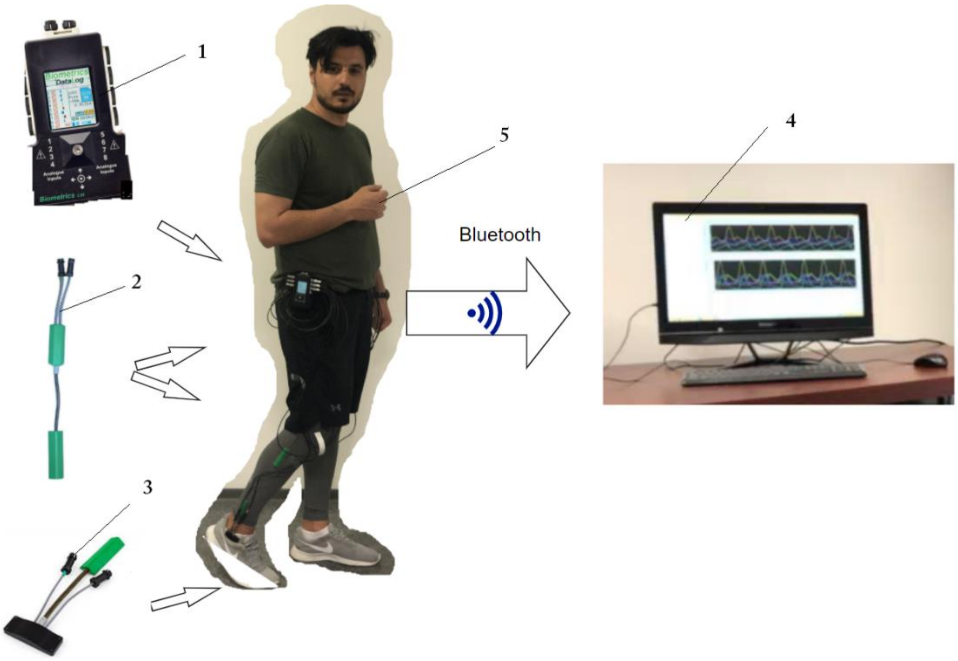


Fig. 1. Schema block of data collection: 1-DataLog device; 2- electrogoniometer SG150 for knee and hip; 3- electrogoniometer SG110, for ankle; 4- diagrams displayed on screen; 5-subject.

The equipment used in the experimental protocol is composed of two DataLOG devices, computer and six electrogonimeters (Fig. 2).

Fig. 2. (a) electrogoniometer; (b) The equipment mounted on a subject during experimental test.

Figure 3 shows the graphical interface of the Biometrics software, used for configuring the electrogoniometers and real-time monitoring of the experimental data collection process. The data is saved in ASCII format in files with the extension .log, but they can also be converted to .txt or .csv format and, later, imported into other applications for their analysis.

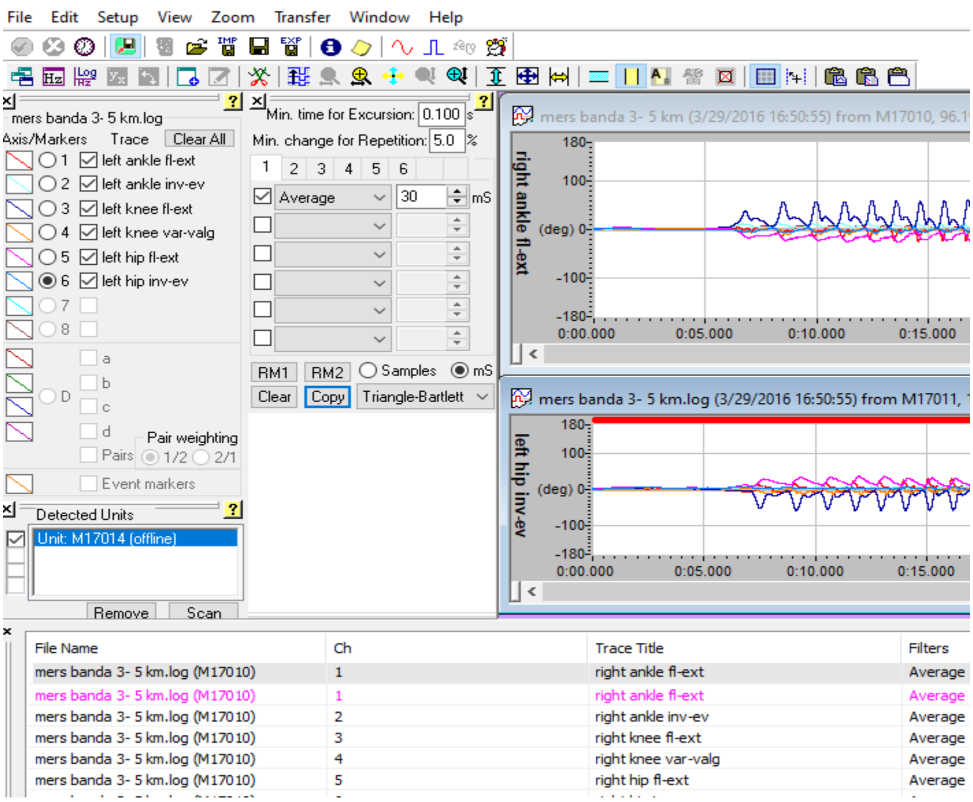


Fig. 3. Interface between user and Biometrics software.

2.2. Subjects

A sample of 11 healthy subjects performed the experimental tests. The subjects did not present any condition that could affect walking, they did not present pain and they did not have any surgical intervention that could affect the quality of walking. The experimental study on human subjects was approved by the Human Ethics Research Committee of the University of Craiova. The anthropometric data of the subjects are presented in Table 1.

Table 1. Average anthropometric data of subjects sample

	Age [years]	**Weight [kg]**	**Height [cm]**	**Lower limb length [cm]**
Average (StdDev)	29.45 (1.67)	73.78 (5.83)	178.32 (7.59)	81.57 (8.21)

2.3. Experimental tests

The subjects performed 10 walking tests on horizontal and inclined TM, with 2 different speeds and 5 different incline angles. The experimental tests performed by healthy subjects on the TM are presented in Table 2:

Table 2. Experimental tests performed by healthy subjects

Slope [degrees] / **Speed [km/h]**	**0°**	**3°**	**7°**	**11°**	**15°**
5	T1	T2	T3	T4	T5
10	T6	T7	T8	T9	T10

A number of 10 tests × 11 subjects × 2 joints = 220 files were collected from all subjects and analyzed. In order to compute the medium normalized cycles of flex-ext corresponding to each data file, SimiMotion software was used [26].

3. Results

The variations of flex–ext angles of the two joints of each subject were obtained for each test. In Fig. 4, consecutive cycles of flex-ext angles in respect with time [s], of Subject 1 for Test 1 (T1), collected and computed by Biometrics, are shown.

By considering the natural human biological variability, which means the stride-to-stride fluctuations in human walking for each individual, and in order to obtain good results, a number of fifteen consecutive cycles were selected inside the walking sequence for each data file, after the two sides of the walking sequence was cut. Then, the fifteen cycles are normalized by using the SimiMotion software [26]. Each of all fifteen cycles are reported at an abscissa of 100 percent and finally, the medium cycle of each file is obtained by the software. By running through the collected data processing algorithm, the average cycles for the 4 joints were obtained for all subjects and for all ten tests.

In Table 3 the average values of main kinematic parameters for all ten tests are measured and computed.

Table 3. Average values of main kinematic parameters computed for the ten tests.

Incline / Speed		**5 km/h**	**10 km/h**
Parameters			
0	**time [s]**	55	55
	distance [m]	77	153
	repetitions	54	110
	No. step/s	1.019	0.50
	frequency [s/no.step]	0.982	2.00
3	**time [s]**	55	62
	distance [m]	77	160
	repetitions	52	110
	No. step/s	1.06	0.56
	frequency [s/no.step]	0.95	1.77
7	**time [s]**	48	65
	distance [m]	66.62	166.56
	repetitions	47	100
	No. step/s	1.02	0.65
	frequency [s/no.step]	0.98	1.54
11	**time [s]**	55	60
	distance [m]	77	166.56
	repetitions	53	110
	No. step/s	1.04	0.55
	frequency [s/no.step]	0.96	1.83
15	**time [s]**	62	60
	distance [m]	86.056	166.56
	repetitions	60	120
	No. step/s	1.03	0.50
	frequency [s/no.step]	0.97	2.00
Average	**time [s]**	55.00	60.40
	distance [m]	76.74	162.54
	repetitions	53.20	110.00
	No step/s	1.034	0.552
	frequency [m/step]	0.968	1.829

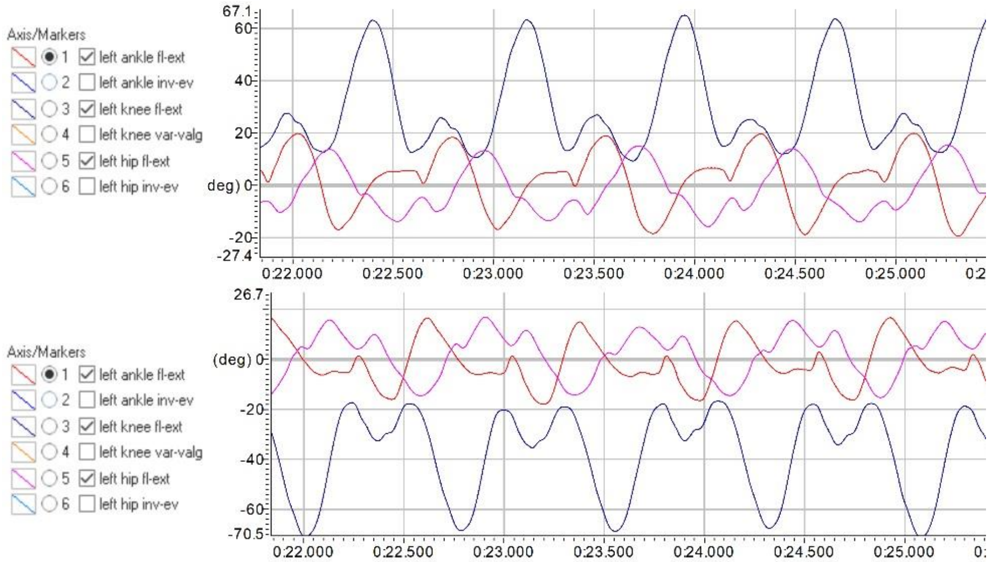


Fig. 4. Diagrams of consecutive cycles of flex-ext angles plotted by Biometrics software based on experimental data collected for both hips, both knees and both ankles - Subject 1, Test 1.

One method to determine the frequencies present in a signal of a time series is to represent the data in the frequency domain. The frequency domain presents data as a function of the frequencies contained in the signal as opposed to the time domain which presents it as a function of amplitude over time. Frequency domain analysis is widely used to provide additional information about healthy and pathological motion. There are many transforms from the time domain to the frequency domain, but the most commonly used is the Fourier transform. The plot of power at each frequency, called the power spectrum, allows you to identify the frequency that contributes the most just by examining the peak positions in the power spectrum. If the peak corresponding to a certain frequency is very large, then the signal of interest has a component at that frequency. The figure 4 shows power spectrum plots of the time series with the measurements taken for the right leg of Subject 1 in the T1 test for ankle flexion-extension movement.

The highest amplitudes obtained in the power spectrum represent the dominant sinusoidal signals in the motion waveform of the joint. By analyzing the figure 5, it can be seen that the dominant frequency for ankle joint of the right leg of subject 1 in the treadmill walking test T1 was 0.985 Hz, that is a cycle of about 1 second. In a similar way the dominant frequency for each test is obtained.

In Fig.6 the mean cycle, mean cycle + StdDev, mean cycle – StdDev for the right and left ankle joints of Subject 1 (S1) for tests T2, T3, T9 and T10 are presented. In these diagrams, StdDev means Standard deviation.

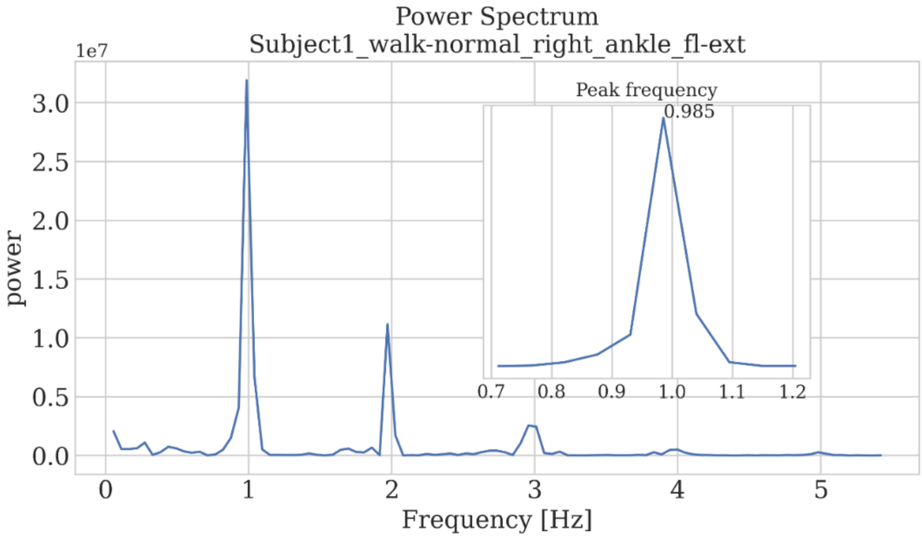
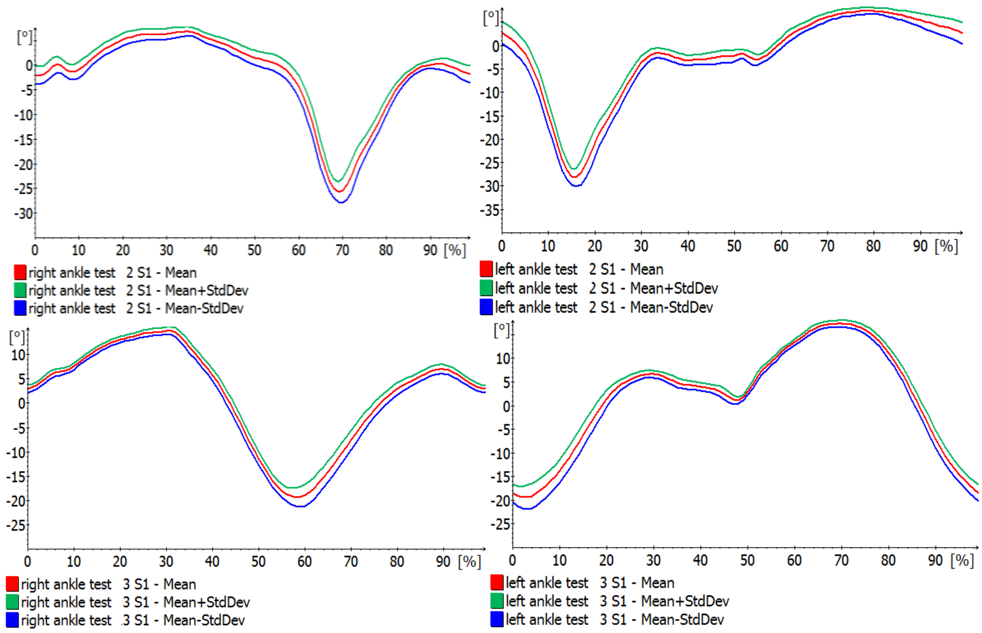


Fig. 5. Time series power spectrum with measurements taken for the right ankle flexion-extension movement of Subject 1 in the normal walking test.



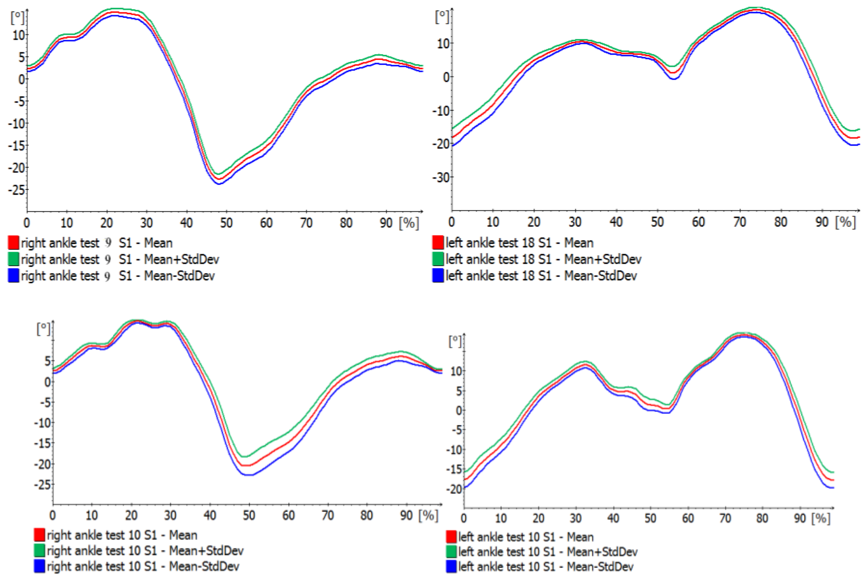
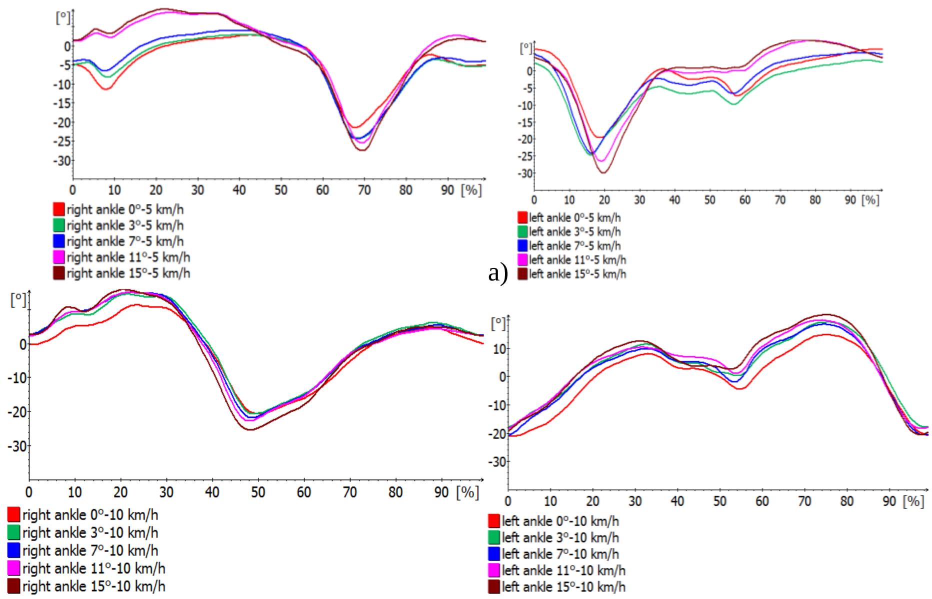


Fig. 6. Mean cycle, mean cycle + StdDev, mean cycle – StdDev cycle for both ankle joints, Subject 1 (S1) – Test 2, Test 3, Test 9 and Test 10

In Fig.7, comparative diagrams of the average cycles of flex-ext angles of sample, function of TM incline angle for a TM speed of 5 km/h and (Fig.6 a), respectively, of 10 km/h (Fig.6 b), are presented.



b)

Fig. 7. Mean cycles of both ankles for the TM incline: 0°, 3°, 7°, 11°, 15°: a) speed of 5 km/h; b) speed of 10 km/h

In Table 4, the average values of flex–ext amplitude of both ankles for the sample are shown, while in Fig. 8 these values are plotted.

Table 4. Average values of flex–ext amplitude for the right and left ankles of sample

Test	**Left ankle [º]**	**Right ankle [º]**
T1	26.1	24.8
T2	27.2	27.7
T3	29	29
T4	35.5	35.1
T5	36.5	37.6
T6	33.9	33.1
T7	35.4	35.6
T8	38.3	37.5
T9	38.5	39.3
T10	40.5	41.1

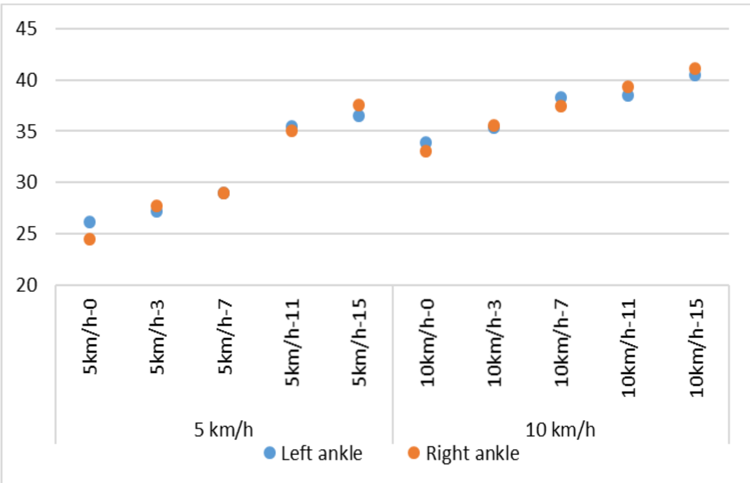


Fig. 8. The average values of flex–ext amplitude [º] for both ankles, for all tests

The diagrams show that, for the same incline angle, the flexion–extension angles of both ankle joints increase by 4-9°, with the increase of the walking speed from 5 km/h to 10 km/h, the differences being bigger as the incline increase. The maximum values of the right ankle varies from 25.8° reported for horizontal TM and 5 km/h to 41.1° for an incline of 15° and 10 km/h. For the left ankle, the maximum value of flex–ext angle varies from 26.1°, related for horizontal TM and 5 km/h until 40.5°, corresponding to an incline angle of 15° and 10 km/h (Fig. 8). The values corresponding to the left ankle are very close to those obtained for right ankle.

For the speed equal to 5 km/h TM the maximum value of ankle flex–ext angle increases by 10–11.5°, while for 10 km/h TM speed, the angle increases by 6-8°, with the increase of the TM incline from 0° inclination to 15° inclination.

The classical graphs of the biomechanical time series collected during experimental tests for different human joints show the variation of the angular positions of these joints in relation to time and do not provide sufficient information regarding the dynamics of the system. The phase plane portraits are 2D graphs that correlate the angular positions of the studied joints (represented on the abscissa) with their corresponding angular velocities (represented on the ordinate). In Fig. 9, 2D phase-plane plots are shown for 6 tests performed by Subject 2 for: a) right ankle and b) left ankle. Similar curves were obtained for all subjects.

From Figure 9, one can be seen that the phase portraits represented for the horizontal TM show a more pronounced convergence in their trajectories, they are more compact, while the trajectories obtained for the 10^o inclined TM are more divergent, they do not overlap on a smaller space and their spread is increasing. It can be seen that the phase planes are almost concentric curves.

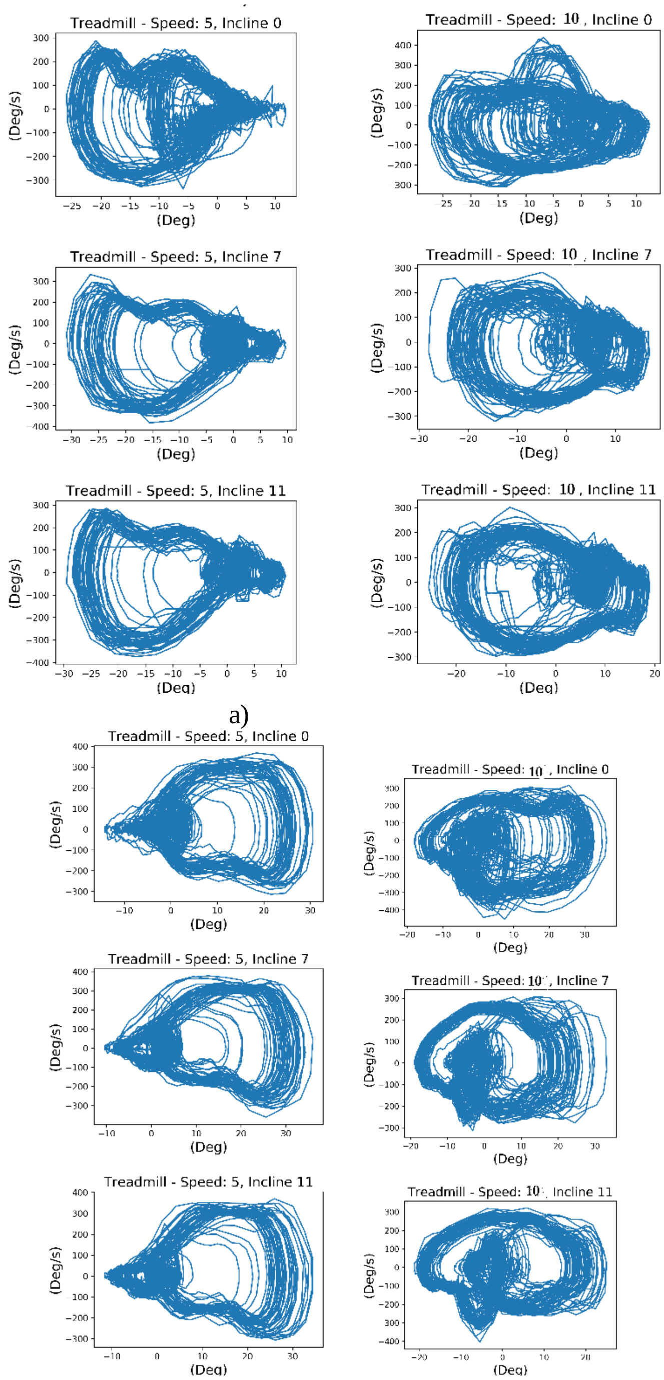
At normal speed of 5 km/h the amplitude of consecutive steps tends to be constant, while at high speed of 10 km/h the amplitude varies.

4. Discussions and conclusions

In this article, we aimed to study the influence of the variation of inclination and walking speed on the flexion-extension angle of the ankles in healthy subjects. Kinematic changes in ankle flexion angles were studied during 10 experimental TM walking tests, depending on TM speed and incline.

The average cycle was calculated for each test, for each subject, and for the entire sample. A comparison is made between the average cycles of each test obtained for the sample. Increasing the TM inclination leads to an increase in the maximum value of the flex-ext angle. In this study, we used the Biometrics system for acquisition and processing the biomechanical data, system based on wearable electrogoniometers in order to evaluate the range of motion of human joints and the changes record in their kinematics as influence of increase of TM speed and inline angle.

The advantages of using electrogoniometers on experimental evaluation are that are not dangerous for human body, they can be used outside the laboratory for daily activities, for monitoring the performance in sport, for diagnosing and monitoring the evolution of different diseases, they are easy to be mounted and to be accepted by the subjects. The results can be used as a data base for future studies including both healthy subjects



b)

Fig. 9. Phase plane portraits plotted for Subject 2, tests: T1, T4, T5, T6, T9, T10, for a) right ankle; b) left ankle

and patients whose ankles are affected, taking into account the importance of this type of human joint, its complexity. In the same time, the ankles are supposed to a big exposure to the dynamic shocks during walking or running overground and on treadmill, and the effects of instability and even, fall, over the quality of patients' life lead to a big risk of morbidity or mortality especially for the older people.

For future work, an increased number of subjects, as well as samples of patients suffering of musculo-skeletal diseases, like stroke or Parkinson disease, will be considered for the biomechanical evaluation, and new parameters will be considered, like age, walking surface roughness and structure, emotional factors, in order to identify multifactorial changes in human gait biomechanics.

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