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Experimental study of the treadmill inclination influence on the flexion angles of the lower limbs joints

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Abstract. This paper presents an experimental study of the flexion-extension movement of the human lower limb joints. Measurements were performed on a group of fourteen healthy subjects, experimental data being obtained for flexion-extension cycles during five different walking tests on horizontal and inclined treadmills. Experimental data were obtained using the Biometrics system, which is based on electrogoniometer sensors. Average cycles for each joint were obtained for all subjects in the experimental group and for all experimental tests. The flexion-extension angles at the lower limbs joints have a pronounced increase with the increase of the walking speed, but also with the increase of the treadmill inclination.

1. Introduction

In the last years, the importance of measuring and analyzing of gait variability has increased and it is more recognized and used in biomechanics and in clinical research field. Spatial and temporal parameters of gait provide useful diagnostic and therapeutic information. In the medical field, the knowledge of gait characteristics, the monitoring and evaluating changes in human gait reveal important information about measurement of the different gait parameters and about the evolution and early diagnosis of different diseases [1-5]. A large number of studies demonstrate the advantages, the accuracy and the validity of the wearable sensors in order to measure and analyze the different parameters of the normal or pathological human gait [1-10].

Temporal-distance measures of gait have been used to evaluate gait function and dysfunctions in the elderly and fall prediction [6, 7]. Many studies that investigated the relationship of gait speed and variability were conducted using different walking speeds measured from overground walking [8]. Slower walking speeds lead to improved local stability, while faster speeds lead to greater instability [9-12]. In healthy adults, the kinematics of walking are more variable as people walk slower or faster than their preferred speed [9, 10, 13].

Motorized treadmills are widely used in research in biomechanical studies of human locomotion or in clinical therapy [12-16]. Both walking types, overground and on treadmill, present small differences in kinematics and kinetics [15], while treadmill locomotion induced shorter step lengths and higher cadences than walking overground at the same speed [13-16]. In [13] the differences between overground and treadmill walking in terms of stride-to-stride variability are characterized. Biomechanics research in gait has focused largely on walking on the horizontal [17, 18], but the number of the paper studying the walking on inclined surfaces are smaller [19-21]. The latter is



important to understand the causes of slips and falls, rehabilitation requirements, prosthesis and orthosis design, as well as robotic structures design and optimization [16, 18-28]. Studies of temporo-spatial and joint kinematics have reported that walking speed and stride length decrease with increasing incline walking down [19, 21] and that stride length increases with increasing incline walking up [19, 20]. Paper [23] shows that, compared to horizontal walking, walking on an incline requires exertion of greater forces across the hip, knee and ankle, and greater ankle motion. These observations are important for disabled or elderly people who are limited in their movements [23]. The objective of this study is to measure the variation of flexion-extension angles of the human legs joints in the sagittal plane while the subjects perform five walking tests, with a speed equal to 7,5 km/h and five different incline angles of treadmill. A comparison between the average cycles of each test obtained for the entire group of 14 subjects is made and conclusions are formulated.

2. The experimental protocol

2.1. Subjects

A sample of healthy subjects was selected for the study - composed of 14 subjects, of which 8 male subjects and 6 female subjects. Prior to testing, all subjects were trained to prevent injury during the tests. All subjects wore equipment suitable for tests consisting of shorts or sports pants, T-shirt and sport shoes. Each of subjects and patients gave their written consent for voluntary participation in the experimental study after being informed of how the study was to be conducted. The conduct of the tests was approved by the Ethics Committee of the University of Craiova. Subjects' anthropometric data are found in Table 1.

Table 1. Anthropometric data of the subjects.

Subject	Sex	Age [years]	Weight [Kg]	Height [cm]	Leg length [cm]	Hip-knee length cm]	Knee-ankle length [cm]
Subject 1	M	26	79	185	90	46	44
Subject 2	F	27	55	168	71	36	35
Subject 3	M	26	71	179	85	43	42
Subject 4	F	28	53	165	69	35	34
Subject 5	M	26	75	182	89	46	43
Subject 6	F	30	53	162	68	35	33
Subject 7	M	26	73	178	86	44	42
Subject 8	M	30	80	181	89	45	44
Subject 9	M	26	82	182	90	46	44
Subject 10	F	27	54	167	70	36	34
Subject 11	M	26	75	180	86	44	42
Subject 12	F	26	56	169	71	37	34
Subject 13	M	26	83	180	87	45	42
Subject 14	F	26	53	162	68	35	33
Average		26,86	67,29	174,29	79,93	40,93	39
StdDev		1,46	12,50	8,27	9,52	4,83	4,72
Cv [%]		5,44	18,58	4,74	11,91	11,79	12,11

2.2. Experimental tests

Tests were performed using the Biometrics system. An important feature of the system is the visualization of diagrams of collected data in real-time. The ability to choose the frequency of data collection has allowed the acquisition of a large number of data and high accuracy. Following several comparative data acquisition tests with different frequencies, the frequency of 500 Hz was chosen to be optimal both in terms of accuracy and the number of data collected in the time unit to perform the

walking tests. The collected data is recorded in real time in the form of data tables and in the form of simultaneous charts corresponding to each active acquisition channel, and at the bottom of the screen there are entered different data such as: number of repeats, maximum value, minimum value, average value, time. Before each test, all channels are set to 0 using the Biometrics software. Data collection is made by activating the Start Data Transfer command, and the data acquisition is completed by the Stop Data Transfer command.

All subjects adjusted to the specificity of the tests by executing them several times before the records with the data acquisition system, leading to their correct and accurate execution.

Subjects performed 5 different walking tests on the moving tape with different tilts. In Table 2 there are presented the tests performed by healthy subjects on the treadmill.

The tests performed by the subjects were carried out in the Laboratory of Biomechanics Research within the Research Platform of the University of Craiova, INCESA.

Table 2. Walking tests on the treadmill.

Incline	0°	3°	7°	11°	15°
7.5 km/h	Test 1 (T1)	Test 2 (T2)	Test 3 (T3)	Test 4 (T4)	Test 5 (T5)

2.3. Equipment

The software used to collect test data was Biometrics DataLog. It allows data collection in both analogue and digital format. In the present study, we used the data collection in ANALOGIC system. The entire data collection process is performed in real time, allowing the digits to be viewed on the software interface. For data acquisition an 8-channel DataLOG at a frequency of 500 Hz (MWX 8 Biometrics Ltd) was used. DataLOG was connected with each platform and the data were transferred from DataLOG to computer in real time via Bluetooth communication. For measuring angles variation during trials, six flexible electrogoniometers connected with the second DataLOG were used.

The data collection process is simple, the subject-mounted electrogoniometers transmit data via the cables to DataLog and the DataLOG converts the received signal and sends it via Bluetooth to the PC, all done in real time. The block diagram of the data acquisition process is shown in Figure 1.

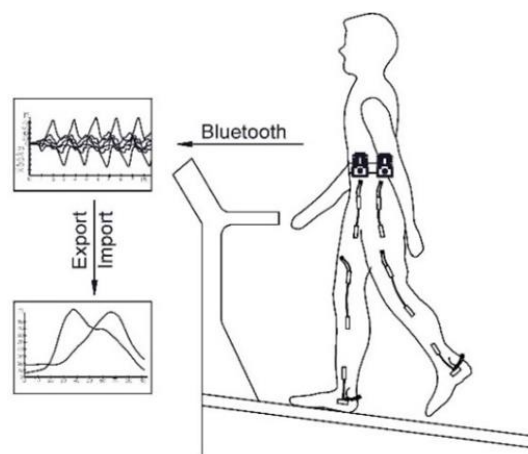


Figure 1. The block diagram of the data acquisition process.

In Figure 2 the data acquisition system mounted on the subject and the virtual mannequin model are shown.

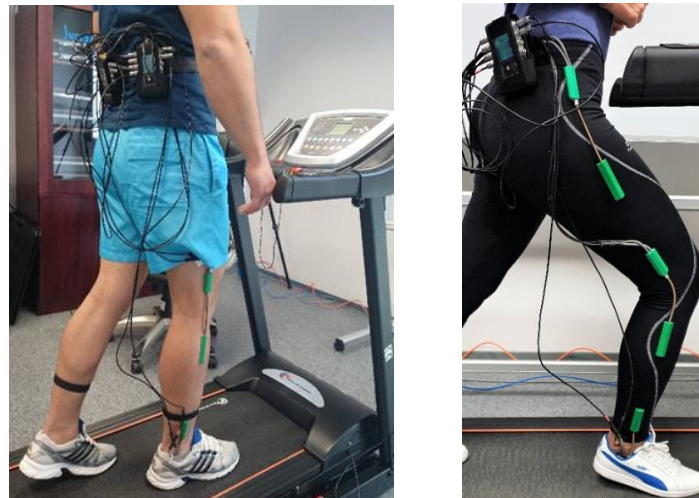


Figure 2. Experimental data collection from electrogoniometers and force platforms in real time.

In Figure 3 the variations of the flexion-extension angles in sagittal plane and of the rotation angle in the frontal plane for the hip, knee and ankle joints of both lower limbs of subject 1, based on the experimental data, are presented.

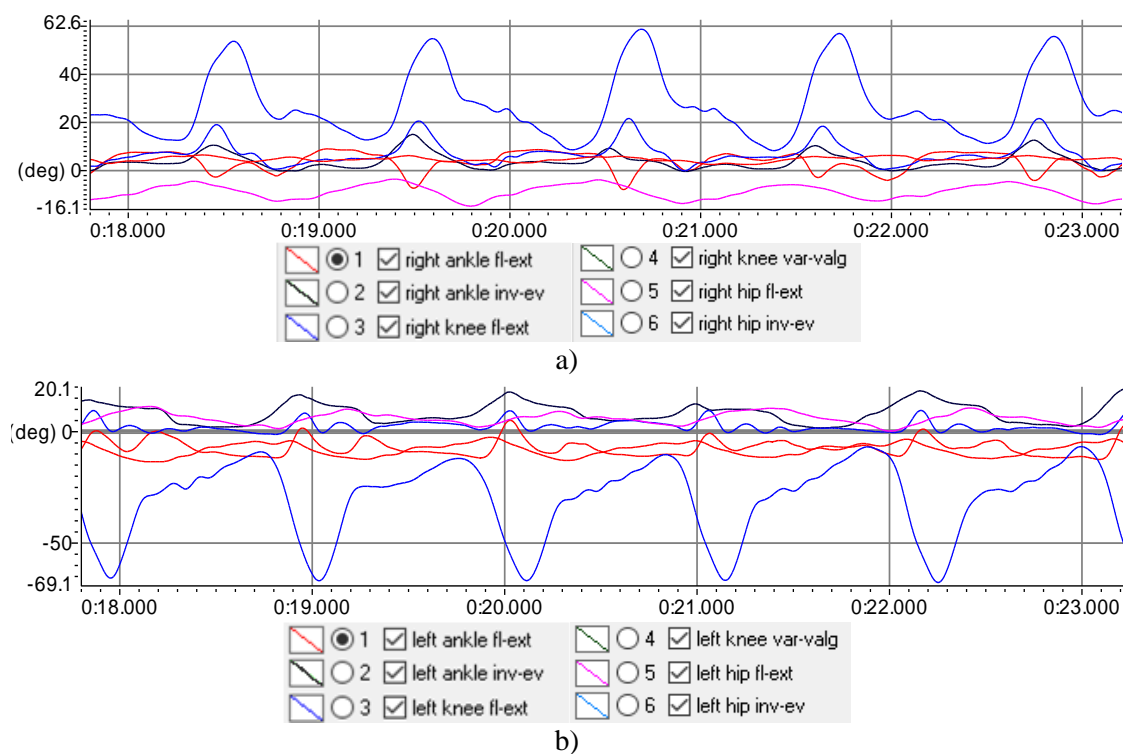


Figure 3. Diagrams of consecutive cycles of variation of flexion-extension angles in the sagittal plane and rotation in the frontal plane represented by the soft based on experimental data collected for hip, knee and ankle: a) right lower limb; b) left lower limb.

An important step in the correctly collecting data is to set the acquisition frequency, the device used in the acquisition, and the name of the acquisition channels.

These settings are done in the Setup DataLOG Analogue Inputs window, accessed from the Analogue Inputs for Recording button (Figure 4).

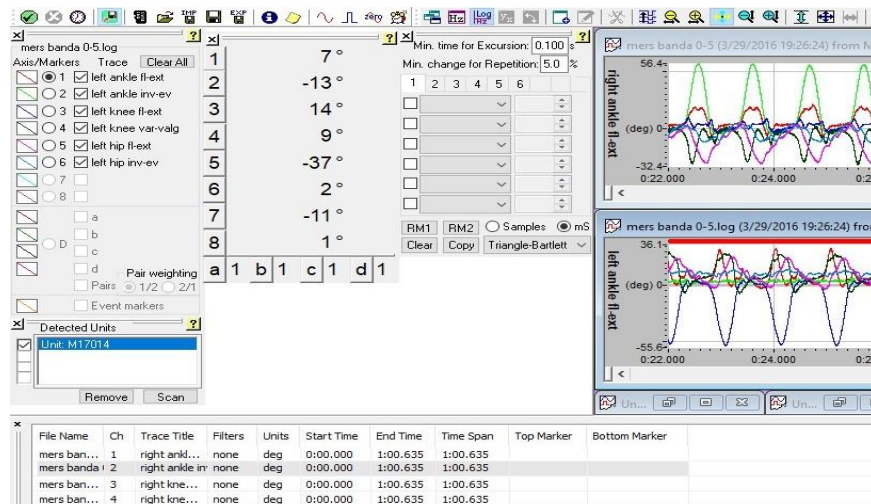


Figure 4. Real-time data capture interface for experimental data.

In the "Setup DataLog Analogue Inputs" command, there are configured the eight channels for each DataLog.

3. Results

A number of $5 * 14 = 70$ tests performed by 14 healthy subjects were performed in the study. The number of files collected for flexion-extension of all lower limbs joints is equal to $70 * 6 = 420$. For data processing, the SimiMotion software was used to import the experimental data files collected with the Biometrics data acquisition. Data processing in SimiMotion results in the average normalized cycles corresponding to each processed data file. Each imported file was divided into phases and consecutive cycles of walking, as shown in Figure 5. The phase and cycle division operation are performed only for one of the reference joints and the diagrams of the average cycles for the other joints will be automatically reported by the software to the reference joint. In this research, the knee joint was adopted as the reference joint for the division into phases and cycles. The phase division is done after eliminating the two first and two last walking cycles, meaning the cycles corresponding to the transient walking, keeping the cycles corresponding to a stabilized walking, in order to ensure greater accuracy of the results obtained from the numerical processing.

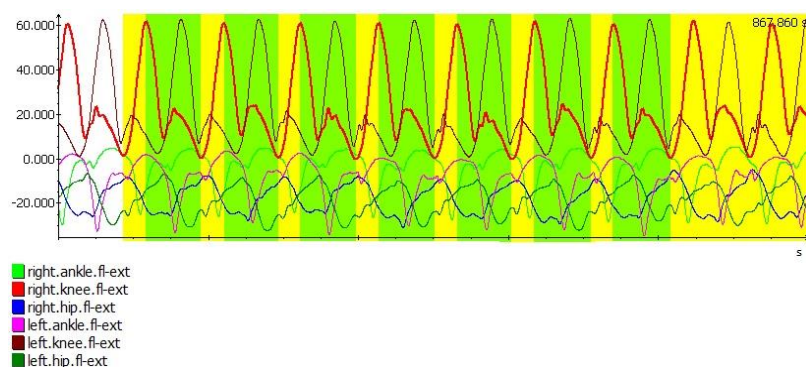


Figure 5. The defined interval used for phasing.

The next step in processing the experimentally data is to calculate the average cycle of the seven consecutive cycles selected for walking analysis together with the corresponding Mean + StandardDeviation and Mean-StandardDeviation curves), the last two curves practically representing the envelopes of the average cycle curve.

The average cycles corresponding to each of the six lower limb joints (both hips, both knees and both ankles) and to each test performed by each of 14 subjects are obtained. In Figure 6 there are presented the average cycles of the flexion-extension angles for each of the six lower limb joints of subject 1 for T4 test (an incline of 11o). Similar diagrams were obtained for each test performed by each subject.

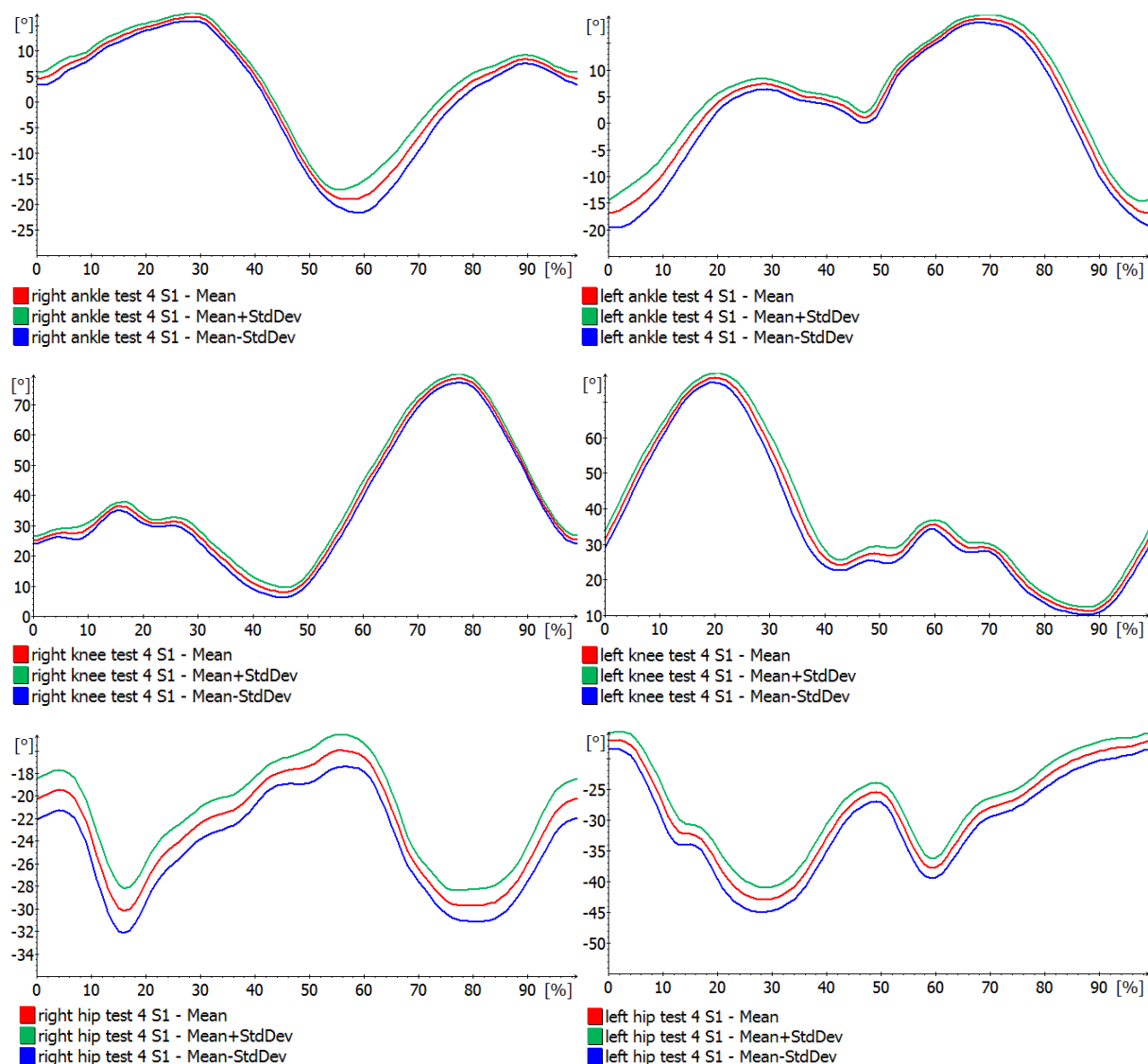


Figure. 6. Average cycles of the flexion-extension angles for right and left ankles, right and left knee and right and left hips, of Subject 1, T4 Test.

For each test, the average cycle of entire group is obtained based on average cycles of each subject. For example, in Figure 7 the average cycle obtained for right knee, T1 test and the average cycles of right knee of all subjects are shown.

For the sample of healthy subjects, comparisons between average cycles obtained for the five tests for all six joints of lower limbs, depending on the incline angle of the treadmill were made (Figure 8).

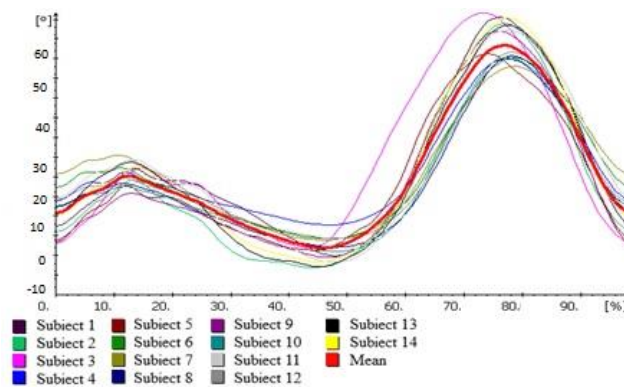


Figure 7. Average cycle of all 14 subjects and of entire group for right knee, T1 test.

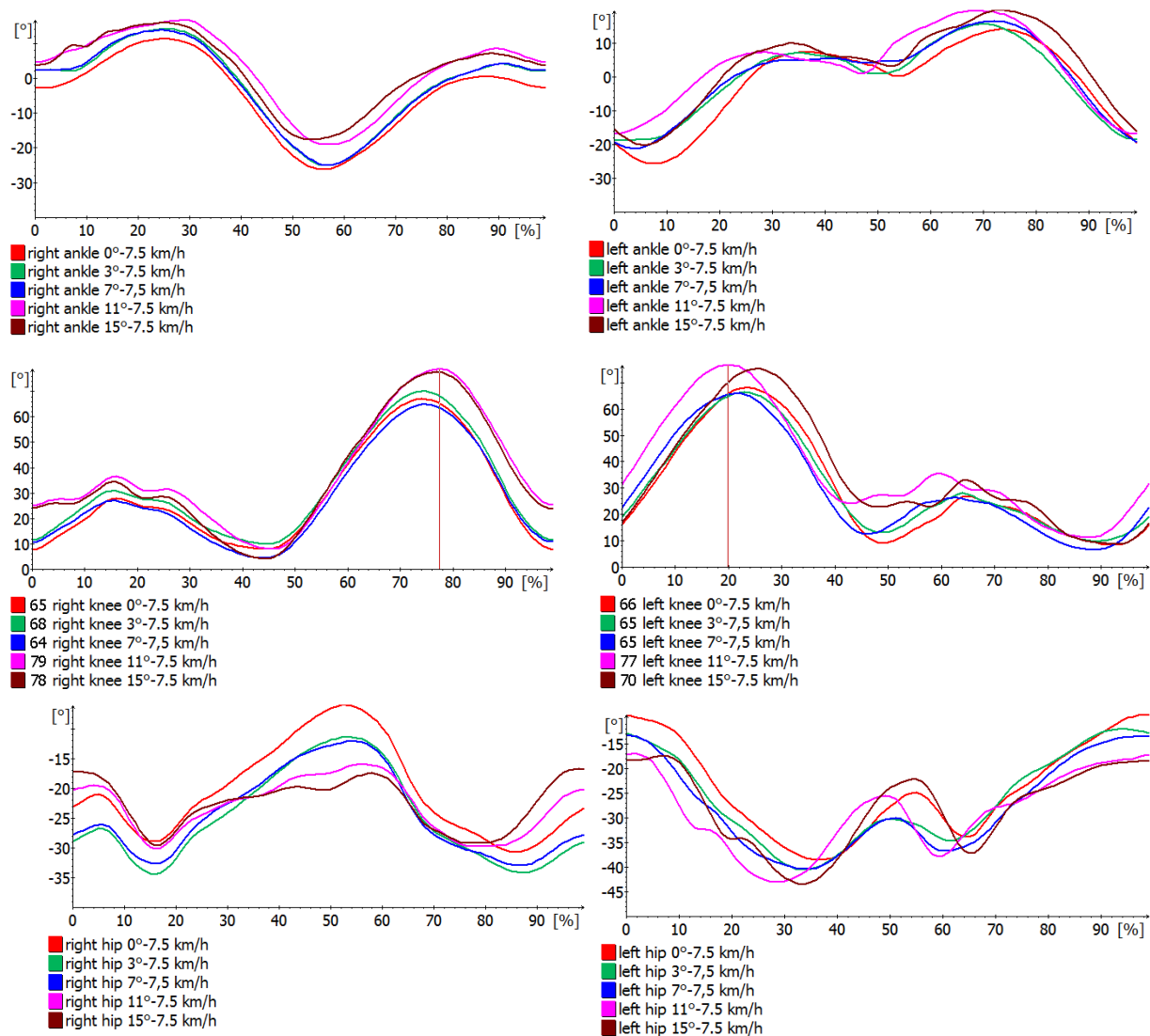


Figure 8. Comparisons between average cycles obtained, for all six joints of lower limbs, T1-T5 tests.

In Table 3 and 4 the maximum flex-extension angle corresponding to the average cycle of right knee and left knee for each subject and each test are presented, while in Figure 9 comparative diagrams of flexion-extension knee angle variation function of treadmill incline are shown.

Table 3. The maximum flex-extension angle corresponding to the average cycle of right knee for each subject and each test.

Subjects Tests	The maximum flex-extension angle corresponding to the average cycle of right knee [°]														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Average group
T1 - 7.5 km/h - 0°	68.6	70.5	64.9	73.3	68.4	65.6	70.1	68.6	70.5	64.9	73.3	68.4	65.6	70.1	68.8
T2 - 7.5 km/h - 3°	71.7	72.6	74.7	74.1	77.1	70.8	69.4	71.7	72.6	74.7	74.1	77.1	70.8	69.4	72.9
T3 - 7.5 km/h - 7°	80.4	70.1	73.7	73.6	80.9	75.7	75.7	80.4	70.1	73.7	73.6	80.9	75.7	75.7	75.7
T4 - 7.5 km/h - 11°	85.2	75.2	80.1	81.6	87.9	83.1	81.1	85.2	75.2	80.1	81.6	87.9	83.1	81.1	82.0
T5 - 7.5 km/h - 15°	89.4	89.6	84.3	83.1	90.0	77.6	78.1	89.4	89.6	84.3	83.1	90.0	77.6	78.1	84.6

Table 4. The maximum flex-extension angle corresponding to the average cycle of right knee for each subject and each test.

Subjects Tests	The maximum flex-extension angle corresponding to the average cycle of left knee [°]														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Average group
T1 - 7.5 km/h - 0°	62.8	64.7	59.1	67.5	62.6	59.8	64.3	62.8	64.7	59.1	67.5	62.6	59.8	64.3	63.0
T2 - 7.5 km/h - 3°	69.2	70.1	72.2	71.6	74.6	68.3	66.9	69.2	70.1	72.2	71.6	74.6	68.3	66.9	70.4
T3 - 7.5 km/h - 7°	75.3	65.0	68.6	68.5	75.8	70.6	70.6	75.3	65.0	68.6	68.5	75.8	70.6	70.6	70.6
T4 - 7.5 km/h - 11°	82.4	72.4	77.3	78.8	85.1	80.3	78.3	82.4	72.4	77.3	78.8	85.1	80.3	78.3	79.2
T5 - 7.5 km/h - 15°	86.6	86.8	81.5	80.3	87.2	74.8	75.3	86.6	86.8	81.5	80.3	87.2	74.8	75.3	81.8

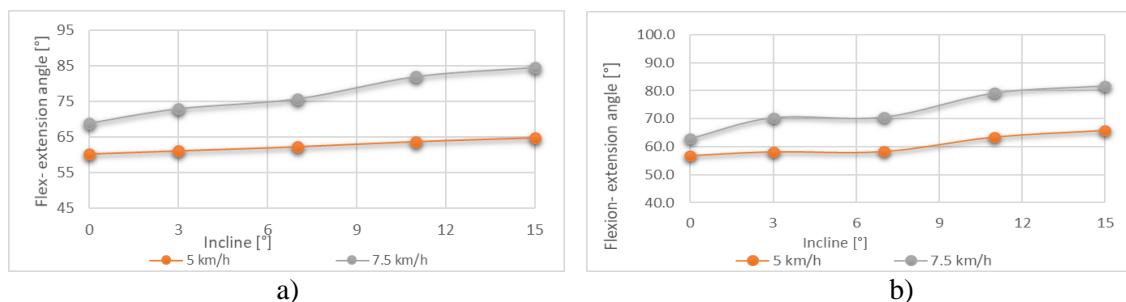


Figure 9. Comparative diagrams of flexion-extension angle variation function of treadmill incline: a) right knee; b) left knee.

From the tables 3 and 4 we can see the increase of the flexion-extension angle with the increase of the treadmill incline. Thus, the extension flexion angle increases with 16-18 ° from 0 degree to 15 degrees inclination, for a speed of 7.5 km/h. In Figure 9 the variation of the flexion-extension angle of the right and left knees is presented according to the walking speed.

An increase of the flexion-extension angle according to the walking speed from 5 km/h to 7.5 km/h with about 8-12 degrees for the horizontal band, up to 15-20 degrees for a 15 degrees inclination is observed. Therefore, the flexion-extension angle of the knee joint has a pronounced increase with the increase of the walking speed and of the treadmill inclination. Similar results and conclusions are obtained for all lower limb joints.

4. Conclusions

The purpose of this research was to study the flexion-extension movements of the human lower limbs joints during five different walking tests walking with fast speed on horizontal and inclined treadmill. A Biometrics system was considered to collect and analyze the data files of flexion extension angles for human ankle, knee and hip joints. Measurements were performed on a group of fourteen healthy subjects. Appropriate graphs were obtained for all subjects in the experimental group for all experimental tests. The flexion-extension angles at the lower limbs joints have a pronounced increase with the increase of the walking speed, but also with the increase of the treadmill inclination. The results obtained in this study are very important for physicists and researchers to study normal and pathological walking, to develop techniques for human joints biomechanics improvement and to develop optimized devices for movements' rehabilitation of lower limbs joints.

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