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Evaluation of Seniors Gait Training with Mechatronic Device

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Abstract

Authors present some results from research work on human movement analysis and its use in clinical practice. The aim of this research was to evaluate the effect of the new rehabilitation method for the prevention of falls in the elderly. The basis of new rehabilitation training is walking disturbed by perturbations embedded in shoes. Perturbations are generated with the original mechatronic device developed within project SMILING - **S**elf **M**obility **I**mprovement of e**L**derly by counteract**ING** falls, no. 215493 granted by the 7th framework program – ICT2007.7.1 „ICT and Ageing“. The SMILING system is a complete system for the training of gait [1]. SMILING shoe is a complex mechatronic system, which requires interaction through data obtained from the sensors of mechanical components, as well as data on user's activities. The SMILING shoes are able to change their configuration during the swing phase of gait to propose a different "ground" when the foot touches the floor. According to the basic idea, the SMILING system is not a medical device but a training device. This means that its use is envisaged also in non-protected environments such as fitness centers and/or private homes. The aim of the pilot study was to assess the impact of unconventional rehabilitation system SMILING on gait pattern. Seventeen patients participated in the study (elderly aged 65 and over) provided in Slovakia in cooperation with the Highly Specialized Geriatric Institute of St. Lukas Košice. Gait pattern has been defined through selected temporal-spatial parameters, obtained by measuring walking self-paced by opto-electrical system SMART in laboratory conditions. The results of the three measurements were compared by paired t-test for significance α=0,05. Data showed that after completing the second stage of training exercises walking speed and the length stride have increased and gait cycle was decreased. However, for approval of efficiency of the new rehabilitation method further clinical testing must be done.

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Keywords: seniosr, fall, neural plasticity, gait pattern, system SMILING. system SMART

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1. Introduction

The seventh most common reason for hospitalization of seniors is injury caused by the fall [2]. One third of all falls in the elderly aged 65 years falls once a year, at with up to two thirds of them fall again [3]. The fall occurs during the execution of some of the physical activity, usually during walking. The literature provides a variety of causes of falls, which are often combined. The fall occurs mainly due to the fact that the impact of aging the degradation mechanisms needed to maintain balance [4]. Several reasons it is possible through clinical examination of early diagnosis and deduces preventive steps.

The basis for primary prevention of falls in the elderly is physical activity. Existing training and rehabilitation methods are based on movement repetition and correction or balance training for standing and not on problem solving for active walking. By applying conventional training interventions to improve walking in elderly at risk of falling some important factors such as the dynamics of the walking motor behaviour and the motor learning processes in the elderly are neglected.

The SMILING system plans to diminish age related impairments through the interference of diminished neural plasticity that limits walking ability and by continuing these functional improvements into real life situations. Researches has shown strong indications that the vicious circle of muscle weakness and time delay in the Central Nervous System (CNS) that causes gait and balance impairment could be weakened by applying unexpected external motion perturbations. These perturbations can loosen stiff walking patterns and hence introduce more flexibility into the motor control system to give improved stability [1].

2. The system SMILING

The SMILING system is complete system that stimulate, train and measure gait in a non-invasive manner aimed at improving walking and thus improving personal autonomy and social participation. It represents a new training approach in the prevention of falls by using an innovative mechatronic system designed to perturb walking performance by changing the environment through the alteration of the ground by means of motorized shoes, able to change height and inclination from one step to the next. It consists of 3 modules [1, 5, 6]:

- a complete walking analysis system
- a motorized pair of training shoes
- a user friendly portable control unit, User Control Unit (UCU)

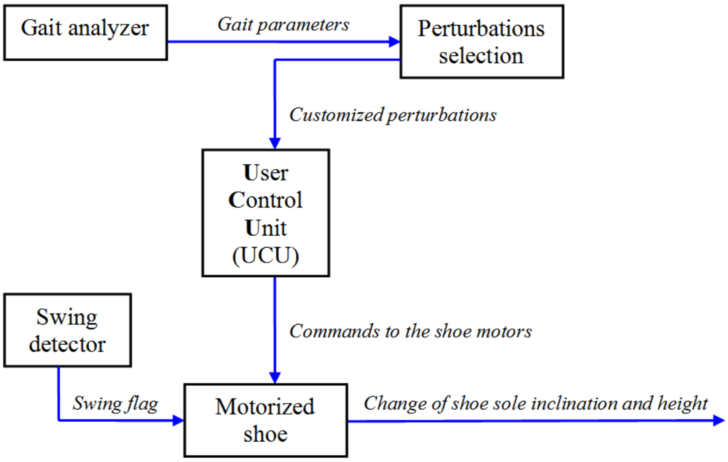

Fig. 1. Function architecture of the system SMILING

To perform gait analysis, a user wears on the back of his/her shoes a wireless sensorized unit, called S-Sense, embedding a 3D gyroscope and a 3D accelerometer. Data from the sensors are acquired in real time and sent to the Operator Control Unit for dedicated processing.

The SMILING user is asked to walk at his/her natural cadence for some minutes to acquire enough data to allow both a linear and non linear analysis of his/her walking features. The computed gait parameters are used by the operator in charge of the SMILING system setup to select the most suitable training exercises for the specific user [1].

2.1. SMILING shoe

SMILING shoe is a complex mechatronic system which requires interaction data obtained from the sensors of mechanical components, as well as data on human activities. Each shoe is equipped with 4 independent DC motors, arranged in pairs in the front and back of the shoe (see Fig. 2). The four motors are activated only during the swing phase to change the position of the actuators while the shoe is unloaded. To identify the swing phase, data are used from a gyroscope, integrated to the shoe structure. The gyroscope is part of the wireless measuring unit S-sense, placed at the back of the shoe.

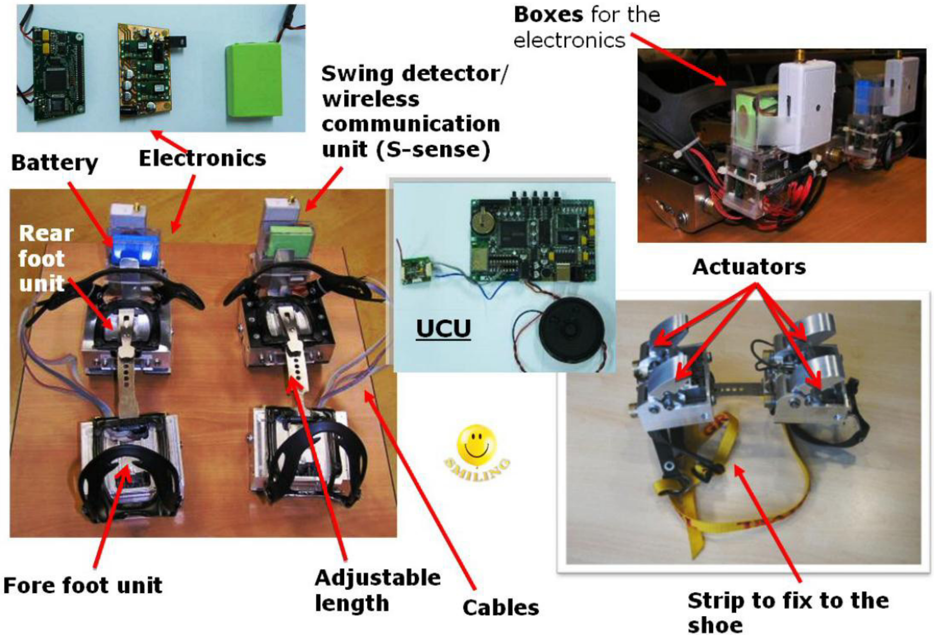

Fig. 2. SMILING system hardware components **Chyba! Nenašiel sa žiaden zdroj odkazov.**

It is intended that the shoe should achieve a combined movement of +/- 4.5 degrees for ankle flexion /extension and +/-4.5 degrees for foot internal/ external rotation in one or two steps made by a user. To achieve this for a user with the largest shoe size, it means that the actuator should rise by a maximum of ~24 mm ideally in a single step. During training, each next position of the shoe is computed by algorithms based on the chaos theory to get unexpectable challenging situations **Chyba! Nenašiel sa žiaden zdroj odkazov.**.

An electronic heart of the SMILING shoe is a microcontroller based on embedded Motor Control Unit (MCU). The MCU stores suitable set of perturbation patterns and drives motors according these perturbations. Driving of motors by MCU is synchronized with a human walking activity that is detected by an external gyroscope processing (S-Sense) unit. The architecture of MCU is optimized for acquisition and fast processing of relevant sensors data and control of mechanical actuators used in the SMILING shoe. Control algorithms embedded in the MCU firmware must be tailored to the parameters and limitations of mechanical actuators used in the SMILING shoe. Optimization of the MCU firmware for tuning of mechanical parts after assembling and durability testing of complete SMILING shoe was also done in order to support integration of all SMILING shoe components (see Fig. 3). The MCU is a typical custom microcontroller system embedded in each SMILING shoe. The MCU performs in each shoe the following basic hardware functionalities [5]:

- interfaces to the S-Sense unit,
- interfaces to the Power Supply Unit (PSU),
- interfaces to 4 incremental encoders monitoring actual actuators positions
- drives 4 DC motors used for actuators movement,
- stores chaotic perturbation data pattern used in current training session,
- monitors reaching terminal positions of 4 mechanical actuators,
- monitors motor currents in order to detect out of expected conditions,

and performs the following software supported functionalities:

- communicates with the User Control Unit (UCU) in order to support remote shoe control,
- communicates with the S-Sense in order to react on swing phase detected by S-sense,
- applies a suitable perturbation pattern to motor control during standard shoe operation,
- monitors and evaluates abnormal sensor data values (e.g. large driving currents and no actuators movement),
- provides background telemetric data channel to the UCU for on-line monitoring of shoe state during normal operation, as well as during shoe testing and tuning.

2.2. Training program with SMILING shoe

The training sessions are managed by the user by means of a devoted control unit UCU. UCU represents interface between users and system Smiling. It is a portable device that the user during training wears around the waist (see Fig. 4(a)). UCU wirelessly communicates in both directions with the MCU (Fig. 4(b)), which allows the transmission of perturbations [1].

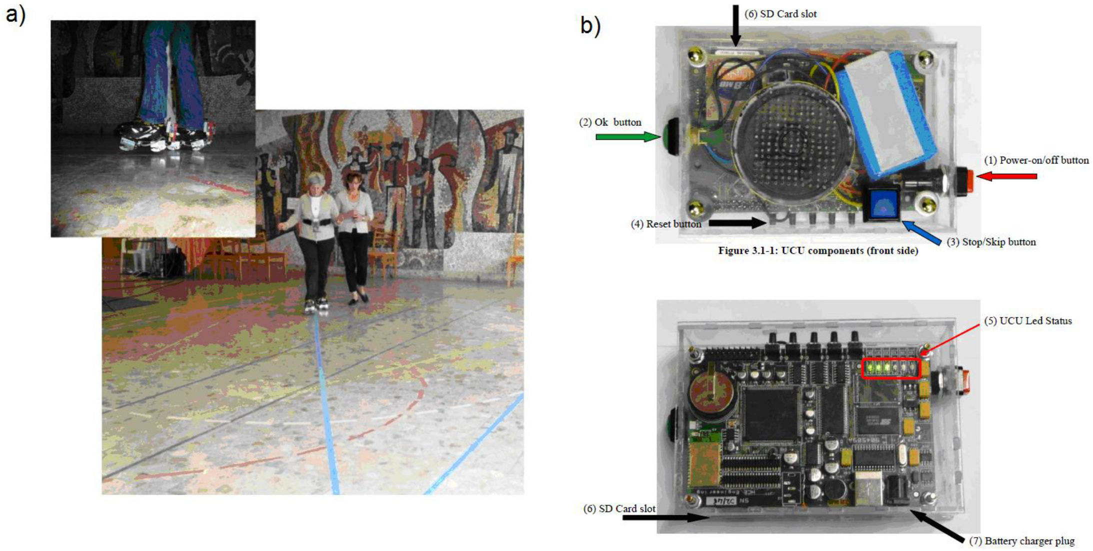

Fig.4. (a) User's training with SMILING shoes following the drawings on the board **Chyba! Nenašiel sa žiaden zdroj odkazov.**; (b) UCU components (front side/rear side) **Chyba! Nenašiel sa žiaden zdroj odkazov.**

MCU downloads, before the start of the training, perturbation patterns suitable for a particular user and collects gait data from the shoes to compute performance indices to provide feedback on the quality of the training performance. During the training the user wears the shoes and the UCU. User activates the training session by pressing a start button. For each foreseen training task, the control unit supplies the main instructions (e.g. "walk for

10 steps counting aloud") and monitors the user's performance. While the user is walking, the unit collects in real time data about the gait performance, computes performance indexes to monitor the training quality and feedbacks the user, e.g. "Very good, you have completely accomplished your task". The collected data on the performance of the user are stored in a SD card [1, 5 ,7, 8].

2.3. Clinical trials with elderly people

Clinical testing was provided in cooperation with the Highly Specialized Geriatric Institute of St. Lukas Košice. The subjects were chosen on the basis of the following inclusion criteria **Chyba! Nenašiel sa žiaden zdroj odkazov.**:

Inclusion criteria

I. Self-reported information:
  - age ≥ 65 years,
  - able to walk at least 20 meters independently, i.e. without personal assistance and without
  - an assistive device, except for a single point cane
  - one or more falls in the previous year (falls during sport activities excluded)
  - no visual and hearing impairments (able to read, watch TV, use a phone, follow a conversation, also with glasses and/or hearing aids)

II. Standardized physical and cognitive functional tests:
  - Tinetti's POMA score between 22-26.
  - Codex examination negative (i.e."very low" and "low probability of dementia")
  - Geriatric Depression Scale (GDS) score (4-items version) = 0

- Group I: 4 weeks of training using the SMILING shoes including perturbations + 4 weeks of training with SMILING shoes but without perturbations;
- Group II: 4 weeks of training with SMILING shoes without perturbations + 4 weeks of training using the SMILING shoes including perturbations (see Fig. 5).

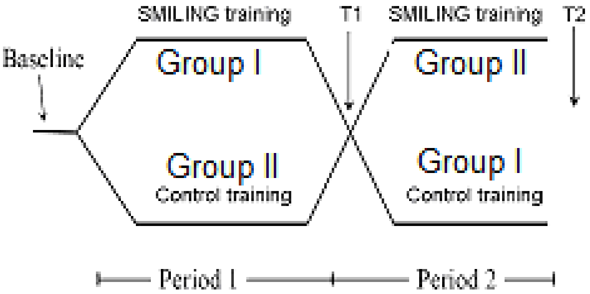

Fig. 5. Clinical trials scheme **Chyba! Nenašiel sa žiaden zdroj odkazov.**

Three measurements were provided (see Fig. 5):
- T0 = baseline
- T1 = after the first training period and before the start of the second training period
- T2 = after the second training period

3. Linear analysis of gait pattern

Patients were selected by the medical staff at the Highly Specialized Geriatric Institute of St. Lukas Košice. Total of 17 elderly subjects in our pilot study in Slovakia. Their mean age was 70,1± 4,34 years, mean weight 70,5 ±

8,69kg and mean height 163,2± 7,88m, Body mass index 26,6±3,49 kg/m^2. Before training were subjects divided in to two groups. Group I consisted of 9 subjects and Group II consisted of 8 subjects. Description anthropometric data, average [± SD; range], group I and II are given in tab. 1.

Table 1. Antropometric data

Gr.	Gender [Female/Male]	Age [year]	BW [kg]	BH [cm]	LLL [cm]	BMI [kg/m^2]
I.	8/1	69,8[3,67; 11]	72,3[9,25; 27]	164,8[5,31; 12]	84,5[10,16; 34,5]	26,7[3,64; 9,9]
II.	7/1	70,4[5,24; 17]	68,5[8,12; 23]	161,4[10,13; 26]	85,4[6,15; 17]	26,43[3,57; 11,7]

3.1. The measurement system: SMART capturing video system

Spatial co-ordinates for the determination of kinematic data were collected using the SMART system (BTS, Italy, version 1.10), which is an automated motion capture system that tracks the position of infrared reflective markers in space. Motion is recorded by 6 infrared cameras in order to reproduce and analyse it in a digital environment. In general, the SMART system is based on the simultaneous recording of the trajectory of small reflective markers attached to the subject's body in well-defined positions via infra-red cameras of high resolution. The cameras were placed around the walking path. Because each marker is simultaneously imaged by several cameras, the 3D coordinates of each marker can be computed. In fact, the cameras send out infrared light signals and detect the reflection from the markers attached to each subject. Based on the angle and time delay between the original and reflected signals, track the movement trajectories of the reflective markers in 3D space. After recording, it is necessary to undertake reconstruction of trajectories of all markers in a digital environment. To determine the movement patterns during walking and their classification, a digital stick model of a human body must be defined.

In the current study, six infra-red CCD cameras, with a sampling frequency at 50 Hz (or 50 frames per second), were used to measure three-dimensional motion of lower limbs for 17 subjects. The three-dimensional bilateral trajectories of 17 reflective markers were monitored by the opto-electric system SMART, which were placed in fixed positions in the examination room, while each subject walked along a 6 meters track.

3.2. Procedure

Before the beginning of the experimental procedure, the experimenter was calibrating the SMART system. Calibration is acquired in order to put a relationship between the positions of the SMART infrared cameras and the space in which the movement will take place. The calibration was achieved by waving a grid with fixed markers. It is necessary for all cameras to recognize the grid markers simultaneously. By waving the grid throughout the entire experimental environment, the volume in which movement was taken place during the data acquisition was determined. This process linearises each camera and measures each camera's position relatively to the others. Then the experimental procedure was composed of three parts:

1. Anthropometric measurements and markers setting
The experimenter measured the subject's height and weight. After the measurements, reflective markers were set on the subject (Fig. 6)

2. Practice period.
Each subject was instructed to walk on the track at his/her comfortable walking speed, starting from the start line which was placed in one side of the track and finishing in the finish line placed in the other side of the track. Each subject walked along approximately 6 meters track.

3. Gait assessment.
Firstly, the experimenter assured that all markers were visible simultaneously from all infrared cameras. Then, the subject started the walking trials at his/her normal walking speed. Each subject performed at least 3 trials.

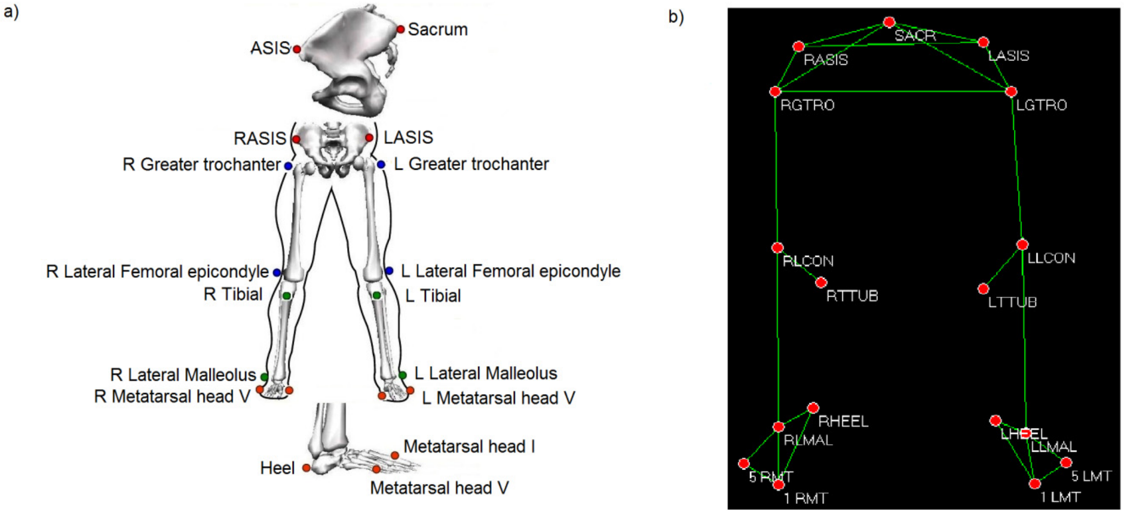

Fig. 6. The marker placement (a) anatomical model; (b) stick model in program SMART Tracker

3.3. Select spatial-temporal parameters

The primary outcome of the study is stride velocity. The reason for this choice is the fact that age-related declines in both gait speed and gait stability have been associated with increased fall risk in older adults. Gait speed during functional walking tasks is slower in older adults with a history of falls compared to those without a history of falls [9]. Stride velocity is also a good predictor for independent living and associated with disability [10] As investigation in the SMILING project found, the community-dwelling older persons walk with speed about 1.2 m/s, SD 0.14 (data from N=864 persons). It was assumed that gain of 0.05 m/s after training shall be considered as clinically significant [1].

The second outcome of the study are gait temporal-spatial parameters. In particular, the gait analysis parameters will include: stride length, gait cycle time, stance phase and phase double support durations, step width (Fig. 7).

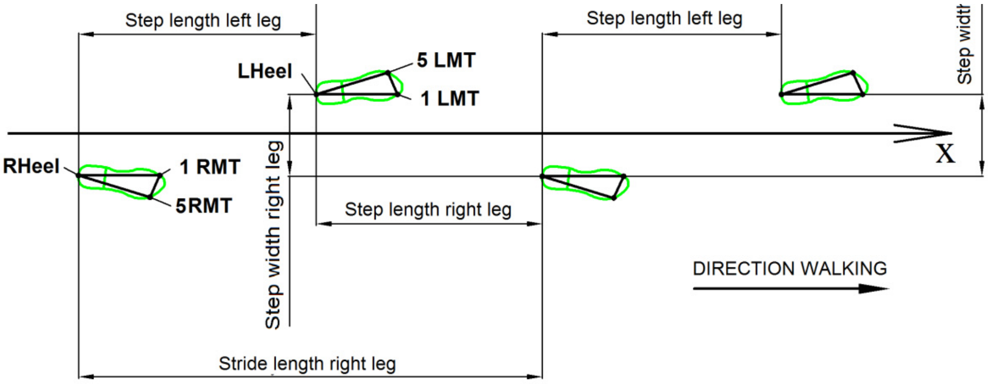

Fig. 7. Spatial parameters

Legend: RHeel - right heel; LHeel - left heel; 1 LMT - left metatarsal head I; 5 LMT - left metatarsal head I; 1 RMT - right metatarsal head I; 5 RMT - right metatarsal head I

3.4. Statistical data processing

The effectiveness of the SMILING training program was assessed using linear gait analysis. Subjects were considered as improvers if they had a positive outcome between two visits, or non-improvers if there was no change or a negative difference. The analysis of improvement/non-improvement was conducted with Student t-test for continuous data. Data processing, numerical and graphical visualization was done in MS Excel and statistical program STATISTICA (Statsoft, version 99).

3.5. Results

In Slovak studied group of seniors was investigated gait pattern in mode of self-paced walking. The temporal-spatial gait parameters were monitored separately for the left and right lower limb. Table 2 shows temporal-spatial parameters (average (A), standard deviation (SD)) at each stage of testing (T0, T1 and T2).

Table 2. Temporal-spatial parameters gait

Variables	Period testing	GROUP I				GROUP II			
		Right		Left		Right		Left	
		A	SD	A	SD	A	SD	A	SD
Stride length [m]	T0	1,21	0,05	1,22	0,06	1,24	0,15	1,24	0,15
	T1	1,19	0,11	1,18	0,11	1,23	0,07	1,23	0,08
	T2	1,23	0,08	1,24	0,09	1,28	0,09	1,27	0,09
Time stride [s]	T0	1,14	0,1	1,12	0,1	1,16	0,17	1,16	0,16
	T1	1,15	0,08	1,15	0,08	1,2	0,15	1,2	0,15
	T2	1,1	0,09	1,1	0,09	1,13	0,18	1,14	0,18
Wide step [m]	T0	0,08	0,01	0,09	0,02	0,09	0,05	0,09	0,05
	T1	0,09	0,03	0,1	0,02	0,09	0,03	0,1	0,02
	T2	0,11	0,05	0,09	0,02	0,1	0,02	0,09	0,02
% duration stance phase	T0	59,56	1,98	59,19	1,68	59,5	1,59	59,96	1,1
	T1	60,12	1,43	60,21	0,88	59,5	1,62	59,38	1,61
	T2	59,75	0,82	59,57	0,91	58,83	1,96	59,2	1,52
% duration double support	T0	19,32	2,65	18,89	2,64	18,83	2,61	19,48	2,29
	T1	19,98	2,39	20,41	2,26	19	2,95	19,13	2,67
	T2	19,55	1,16	19,53	1,1	17,77	3,54	18,16	2,79
Walking velocity [m/s]	T0	1,07	0,09	1,09	0,1	1,1	0,25	1,09	0,23
	T1	1,04	0,1	1,03	0,11	1,04	0,15	1,04	0,17
	T2	1,13	0,11	1,14	0,11	1,15	0,23	1,15	0,23

Effect of the walk training on gait pattern was evaluated by matched t-test. The statistically significant difference at a significance level $\alpha = 0.05$ was confirmed after the second period training session, in the case of Group I with four parameters and the Group II in the two parameters (Table 3).

Table 3. *p-value* of temporal-spatial parameters gait.

Variables	Comparison	GROUP I		GROUP II	
		Right	Left	Right	Left
		p-value	*p-value*	*p value*	*p-value*
Stride length	T0 vs.T1	0,40	0,15	0,67	0,89
	T1 vs.T2	0,03*	0,02	0,046	0,09
Time stride	T0 vs.T1	0,62	0,39	0,39	0,39
	T1 vs.T2	0,01	0,01	0,06	0,08
Wide step	T0 vs.T1	0,42	0,01	0,89	0,58
	T1 vs.T2	0,21	0,59	0,78	0,26
% duration stance phase	T0 vs.T1	0,41	0,09	1,00	0,36
	T1 vs.T2	0,47	0,11	0,24	0,58
% duration double support	T0 vs.T1	0,50	0,07	0,89	0,78
	T1 vs.T2	0,63	0,27	0,33	0,26
Walking velocity	T0 vs.T1	0,46	0,26	0,41	0,49
	T1 vs.T2	0,01	0,02	0,03	0,02

*p > 0,05 – statistically significant

The results obtained by comparing selected gait parameters after completing the first series of training exercises showed that improvements were not statistically significant. After the second period of training exercises, it was confirmed that improvements were statistically significant - in the increase of walking velocity in both groups. In group I, there was an increase of walking velocity in the average 0,1m/s and for Group II 0.11m/s. In the case of Group I, it was a symmetrical change in walking speed (a statistically significant difference was confirmed for both - right and left lower limbs). The change in walking speed influenced the increase in the stride length and decrease in gait cycle duration.

4. Conclusion

Based on the results obtained and the data analysis can be stated, that the first series of training exercises in both groups did not cause a change in the gait temporal-spatial parameters to the extent that it would mean a statistically significant difference. Even, there was a decrease in the average walking velocity in Group I of 0.045 m/s and in Group II of 0.02 m/s. However, this decrease was not statistically significant at the significance $\alpha = 0{,}05$.

A statistically significant difference as improvement was observed in both groups after completing the second series of training exercises. However, it should be emphasized that in the case of Group I, it was only a control training without perturbations, at which the effect of training was proved, and even bigger than in the case of group II, which just completed training with perturbations provided by the mechatronic device. It seems that the main factor in our experiments was time of training duration and combination of weight and shape of SMILING shoes. However, clinical testing proved that training with SMILING shoes was effective. Validation of theory that chaotic changes in shoes inclination will be more effective than others methods in gait training of elderly has to be proved with further clinical testing.

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