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Neural model of human gait and its implementation in MATLAB and Simulink Environment using Deep Learning Toolbox

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Abstract. The article presents selected results of research on the modeling of humanoid robots, including the results of neural modeling of human gait and its implementation in the environment MATLAB and Simulink with the use of Deep Learning Toolbox. The subject of the research was placed within the scope of the available literature on the subject. Then, appropriate research experiments on human movement along a given trajectory were developed. First, the method of measuring the parameters present in the experiment was established, i.e. input quantities (displacement of the left heel, displacement of the right heel) and output quantities (displacement of the measurement point of the human body in space). Then, research experiments were carried out, as a result of which numerical data were measured in order to use them for teaching and testing the Artificial Neural Network. The Perceptron Artificial Neural Network architecture was used to build a model of a neural human walk along a given trajectory. The obtained results were discussed and interpreted, drawing a number of important conclusions.

Keywords: Artificial Neural Network, Deep Learning Toolbox, Humanoid Robots, MATLAB and Simulink Environment, Modeling of Human Walking Motion.

1. Introduction

The aim of research conducted in the field of humanoid robotics is to build robots that can be used to support human work, both physical and mental work. A separate stream of research concerns supporting the functioning of the human body or its parts, such as an artificial leg, artificial hand, artificial heart, artificial kidney, and recently even an artificial liver, and even an artificial eye and an artificial ear [20]. Research works on humanoid robots and their elements are carried out especially intensively, among others in Japan, China and South Korea, especially very intensively among others by automotive and electronics companies (for example Honda and Sony). At the same time, there are also attempts to build self-propelled machines, instead of traditional wheelchairs for disabled people, controlled by human thought [7-8, 23, 26-27].

A. Appriou, A. Cichocki and F. Lotte have shown, inter alia, that the estimation of cognitive or affective states on the basis of brain signals is a key but difficult step in the development of passive brain-computer interface (BCI) applications [1]. So far, estimating mental stress or emotions from electroencephalogram (EEG) signals is only possible with modest classification accuracies, which, however, leads to unreliable neuroadaptive applications. However, the latest machine learning algorithms, in particular classifiers based on Riemann geometry (RGC) and the so-called Convolutional Artificial Neural Networks (CNN) proved to be promising, incl. for the BCI system used in motor imaging [4, 14, 22].

In parallel, research is also conducted on bipedal humanoid robots, which are intended for education and experimental research, but are also produced as toys. Some humanoid robots (eg Honda ASIMO) are also oriented towards supporting elderly or disabled people in carrying out daily activities [2]. The conducted research indicates that, in various practical applications, the development of humanoid robots, especially two-legged robots, may soon take place in the area of science and research [6-7, 10-11, 13, 15] and in the area of providing services to the public.

A separate group of humanoid robots are robots already used in the area of uninhabited factories and unmanned objects. This is especially true for applications such as using humanoid robots to transport materials, semi-finished products and finished products between various flexible production lines, not yet fully automated [5, 9, 18, 24-25].

As part of this research trend, research was undertaken to develop a model of the human neural gait system, i.e. an Artificial Neural Network that learns gait on the basis of data captured by two cameras recording human walking along a given path. The position of the left and right legs was adopted as input quantities, and the starting values for the displacement of the point marking the center of the human body are its spatial coordinates. So far, the authors have not come across the results of this type of research conducted on a larger scale in the field of teaching the Artificial Neural Network of human gait with the use of measurement results obtained with a camera.

2. Humanoid robots

In the literature on the subject, a humanoid robot is understood as a machine, in particular a computer system equipped with it, in which the program controls peripheral devices in order to perform an intelligent task [5, 7, 9]. Such a humanoid robot, also known as an intelligent robot, is controlled by computer programs using artificial intelligence methods. Such a control system is often directly called artificial intelligence, and now the concept of artificial intelligence is also used for devices supervised by algorithms or directly by humans.

Thus, in the broadest sense, an intelligent robot or a humanoid robot is any computer program that automates tasks important for control and mobility. Humanoid robots often replace humans in monotonous, tedious, and dangerous jobs that consist of repetitive activities that are performed much faster than human beings could.

Therefore, humanoid robots, consisting of mechatronic devices and computer control systems, can perform tasks that are dangerous for humans, such as those related to the manipulation of chemicals harmful to health or while staying in an environment that is hostile or even inaccessible to humans [3, 5].

The term humanoid robot is also used for robots operating autonomously in the process of receiving information from the environment with the use of sensors. An important role in this respect is played by artificial neural networks, the input neurons of which receive information obtained by means of various types of effectors [14, 19-20].

The field of artificial intelligence dealing with the design and construction of humanoid robots is robotics, and intelligent robots are then called humanoid robots if they resemble humans in appearance and way of existence. Thus, the concept of a humanoid robot is a more general concept than the concept of an intelligent robot. In recent years, humanoid robots have been gaining more and more popularity, because designing a sequence of movements for such a robot is intuitively understandable by relating movements to human movements [3, 7, 10, 23].

Nevertheless, controlling various types of movements and activities of a living organism, which is a human being, is so far a very complex and difficult issue to be implemented in practice. Thus, it is still a huge challenge for laboratories dealing with building bioloids, humanoids, cyborgs, etc. [20].

The research is first carried out on the basis of basic human movements, such as the movement of a human hand or hand, human gait or foot movement, etc. So the research begins with the simplest tasks such as the movement of a humanoid, then gradually more advanced movements are added, such as kicking a ball or standing on your hands and then climbing stairs, or standing up after a humanoid has fallen over [9-10, 13, 15, 18, 24-25].

The commercially available bioloids that are currently being built have the ability to program their movements using appropriate programming languages and programming environments. The experience with humanoid robots is primarily a solid programming school, preceded by an independent model assembly, while planning tasks for a finished robot is a specific test of creativity, especially for young people, including students [7, 10]. So a humanoid robot is a body-shaped robot built to resemble the human body and its behavior. Creating appropriate humanoid robot designs from the point of view of the tasks performed, such as interacting with human tools and the environment, requires long-term training of a humanoid robot in appropriate movements.

3. Modern projects and development of humanoid robotics

Among the achievable features of various humanoid robot solutions available on the market, the following are distinguished: the number of degrees of freedom[2], the type of locomotion system used, and the ability to express facial expressions and emotions. He has been dealing with this type of issues in automation and robotics since the 1950s. More and more robotic devices and elements have built-in computer systems, thanks to which they operate in accordance with the prepared scenario, and more and more often without an appropriate scenario, developing increasingly complex and autonomous decisions in critical situations [10, 28-29].

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[2] In general, the number of degrees of freedom for a kinematic chain is defined as the number of position variables that must be specified to define a system in space. In order to determine the number of degrees of freedom for a kinematic chain, the following formula is used: $w = 6 \cdot n - \sum_{i=1}^{5} i \cdot p_i$,where: n - number of movable members, i.e. the number of pairs of the kinematic chain, i - class number corresponding to the number of nodes superimposed by the connection between two members treated as a six-degree rigid body freedom, p_i - number of connections of kinematic pairs of the i-th class. In practice, the number of degrees of freedom of an open kinematic chain is most often set as equal to the number of fifth class kinematic pairs, rotational and sliding [9, 24].

Among the many tasks related to the appropriate humanoid programming, projects aimed at modeling human behavior can be distinguished. Motivations for this approach vary, but most of these types of projects are based on sociological premises. Human behavioral boosting robots are perceived by humans as being friendlier and better accepted in society.

On the other hand, there are psychological motivations that lead to the consideration and modeling of various aspects of human psychology, including emotions, needs and advanced memory models. In this way, the aim is both to expand psychological knowledge (modeling psychological aspects), as well as to develop more perfect mechanisms of self-adaptation in the constructed technical systems (automation and robotics).

The vast majority of currently designed humanoid robots are focused on cognitive tasks, ranging from object recognition and interaction with them, through issues related to planning the trajectory of robots, manipulators, and executive members, and ending with advanced behavioral strategies.

The most famous humanoid robot designs include:

The **DARPA Robotics Challenge**, which is basically a competition where humanoid robots from all over the world compete. Their main task is to assist people in the conditions of an industrial catastrophe. The competition task consists of eight elements defined as: vehicle (a robot driving a car, has to drive a section of a road with obstacles, then get out of the car and walk away from it), terrain (the robot is designed to overcome three terrain obstacles of varying complexity, starting with from a low wall to an unstable rubble), a ladder (the robot should climb the ladder, then stand on the landing and then go under the crossbeam), rubble (the robot's task is to clear the path between two walls, i.e. remove scattered logs on the way, and then go between the walls, all the way to the door), door (the robot should go through three types of door - pushed, pulled and closed with a handle), wall (using a suitable tool, e.g. controlled by a switch or trigger, cut the desired shape in the wall), valve (the robot must close three valves of different design - a lever, a large wheel valve, a small wheel valve), a hose (the robot has the task is to pull the fire hose to the water tap and attach it to it) [35].

Thus, quasi-stationary humanoid robots are humanoid robots attached to the ground or carried, which are not able to move independently and change their location. Such a robot is, among others **the Japanese Affetto robot**, which was developed in 2011 at the University of Osaka. Its appearance, including the size, resembles a two-year-old. In its behavior, it allows you to express emotions and make faces with an artificial human face, which was made of silicone. Given her limited flexibility by the use of pneumatic actuators that allow the face to touch and pressure, including its grimaces, smiles, and other emotions. The robot was designed for research related to child development and sociological relations between children and adults [36].

In turn, the para-humanoid production robot is a robot called Baxter, whose arms have 7 degrees of freedom (DofF). The robot is equipped with a vision system, sonar and a screen on which emotions can be displayed. This robot is used to conduct research on interactions between a robot and a human, including ways of manipulation and advanced methods of control and perception. At the current stage of research, an Artificial Neural Network, learned under supervision, is used [37].

Research on facial expressions and expression of emotions through the face has been conducted in the USA by the MIT laboratory since the 1990s over the head of a robot called Kismet. This robot is an intelligent robot (not fully humanoid, it does not have a body) that enables natural, interpersonal communication, based on the language of the body and on various types of human motivational elements, such as emotions. It has been equipped with a set of sensors that implement visual, auditory and other skills. It simulates, among others emotions through various facial expressions, sounds and movements, and the facial expressions of the head are created using the movements of the ears, eyebrows, eyelids, lips, jaw and head movements. So far, the robot has been used in research on its behavior during interaction with humans (the so-called Human System Interaction, HSI), and above all to improve the mechanisms of the learning process [38].

Another intelligent robot (also not fully humanoid - it does not have a body from the waist down) is a robot called Simon, which was designed by a team from Georgia Institute of Technology. However, this does not interfere with its practical applications, because the Simon robot is, among others, used in practical research on the issue of machine learning, which consists in identifying signals, creating a model of the environment system on this basis and then repeating the behaviors observed in the environment using the learned model. An additional property of the robot is its ability to interact with the teacher, which is due to the fact that the Simon robot is equipped with a series of flexible motors with very high flexibility. Thanks to them, the robot can squeeze objects with its humanoid hands with varying degrees of force. The robot's head expresses various kinds of emotions in relation to human interaction activities. This makes, among others the Simon robot can participate in games that require communication, including speaking and intelligently recognizing when he is involved in the game and what his behavior should be [39].

The intelligent (not fully humanoid) robot is **the Telenoid robot**, which was designed by Hiroshi Ishiguro - a professor at Osaka University and Advanced Telecommunications Research Institute International (ATR) in the form of a humanoid body with an emotional head.

Its sole purpose is to effectively express the characteristics that make the user feel like they're communicating with another person. The telenoid is controlled remotely by another human whose presence it emulates.

The conducted research proved that its effectiveness in expressing the other person helps (from a sociological point of view) both the elderly and children. Due to specific applications, the robot has only 9 degrees of freedom, weighs 3 kg and is made of a material that perfectly simulates human skin. The research conducted with the use of the Telenoid robot is aimed at perfecting the control of the robot so that its movements seem completely natural [40].

In addition, research is underway on a series of para-humanoid robots **called the Robotic Nursing Assistant System** (RoNASerBotRoNA) developed by designers from Hstar Technologies Corporation, which support medical care for the elderly. The SerBot service robot of the RoNA series carries out various tasks of looking after the elderly, it can carry heavy objects, respond to commands, and even transport the person under its care to another place. Ultimately, the RoNA robot is to have 23 degrees of freedom and a large lifting capacity (on the order of the weight of an adult person). So the main purpose of the robot is to provide assistance, including lifting people who cannot get up or carrying them to bed or bathtub. The robot is additionally equipped with a system of direct communication with the doctor [41].

Another robot worth attention is the robot called **EMIEW 2**, which is a robot produced by Hitachi, designed to move around in an office environment - in particular to follow a person. It therefore acts as an office assistant that can move at a speed of 6 km / h. To ensure efficiency and safety in an office environment, the EMIEW 2 is 80 cm high and weighs 14 kg. The robot was equipped with a 14-channel array of microphones, so that it could clearly determine the direction of the sound and the command given. It also has a laser radar that allows mapping the space around it [42].

Work on humanoid robots is also carried out in Poland, incl. at the Department of Cybernetics and Robotics at the Wrocław University of Technology, which as part of the LIREC project, financed by the European Union from the 7th Framework Program, developed a robot called **FLASH** (Flexible Lirec Autonomous Social Helper). The robot is to act as a life companion - a social robot capable of operating in the human environment and interacting with humans in a natural way. It tries to emulate the appearance and behavior of a human (in some respects), especially the emotional intelligence expressed through facial expressions. However, it is completely dissimilar to the Kismet robot, whose face consists of separate modules of the mouth, eyes, etc. FLASH consists of an EMYS (Emotive Head of a Social Robot) and a body mounted on a two-wheeled platform that moves in an inverted manner pendulums. Thanks to the expression of emotions, the robot can communicate with people much better, and in particular, be better perceived by them [43].

Walking robots constitute an important group of humanoid robots. It is a series of humanoid robots developed by the Center for Robotics & Intelligent Systems at the Birla Institute of Technology & Science, Pilani. The robot called **AcYutAcYut**, proposed by the constructors, has 28 degrees of freedom, can move on two legs, and the installed Firefly MV camera and Inertial Measurement Unit enables it to receive stimuli.

It uses an inertial gauge set with 6 degrees of freedom as a device that measures the speed, orientation and gravitational force acting on the robot, using a combination of accelerometers and gyroscopes. It imitates human sensory organs that help us perceive changes in the surrounding environment. Its purpose is to study methods of controlling advanced walking robots, and to search for teleoperation technology.

Finally, very important robots called **ASIMO** (Advanced Step in Innovative Mobility) are a series of robots produced by Honda Motor Company. The producer's goal was to create a robot that would be helpful in everyday life. ASIMO is about 120 cm tall, weighs 63 kg and is one of the first robots to be fully humanoid robots. ASIMO has 34 degrees of freedom, it can walk upstairs and even run at speeds of up to 6 km / h. Its grippers are adapted to hold objects of various shapes. Additionally, apart from various types of autonomous tasks, ASIMO is also adapted to be controlled by means of thoughts [2, 30].

Without exhausting the very rich subject of humanoid robots, it is also worth mentioning such achievements of automation and robotics as, among others:

- a robot called **Cognitive Humanoid Autonomous Robot** with Learning Intelligence (the so-called Charlie robot) as the first fully humanoid robot, which was constructed in the United States due to its appearance [33],
- a series of robots developed since 1999 by Kawada Industries in cooperation with the National Institute of Advanced Industrial Science and Technology, HRP (**Humanoid Robot Prototype**), which were designed to work with people (the current version of the robot is HRP-4) [32],
- basic robot called **Kobian** developed at WASEDA University in Tokyo, which is designed to interact with people in the course of daily work. The robot has 68 degrees of freedom, 24 of which are intended for facial expressions, and thanks to a specially constructed face, the robot can express 7 basic emotions of varying intensity.
- a robot that can dose the pressure force is a robot called **ASRA C1**, which was developed by Asratecrobot, it is controlled by the V-SIDO system, which allows it to be controlled

by means of: a mobile phone, glasses (the concept of controlling by eyesight - the so-called Corpus Iudicium), joystick-type elements, as well as in the classic motion copying mode, it has 35 degrees of freedom, accelerometer, gyroscope, magnetic sensors, a camera and a Kinect camera, which allow it to recognize human movements during interaction [34].

The next generation humanoid robot, capable of performing tasks requiring high dynamics and high precision, is a robot called Valkyrie, which is being developed at NASA Johnson Space Center, has a height of 188 cm, a mass of over 130 kg and 44 degrees of freedom [31].

The presented overview of sample robots does not exhaust the long list of currently available **humanoids, biloids, telenoids, cyborgs,** etc. There is a clear trend of developing more and more complex humanoid robots, including those equipped with movement (walking, hand movement, facial expressions, communication with the environment, etc.) that is, human and useful human-like robots [28-29].

4. A research experiment in the field of designing an Artificial Neural Network in human gait

In this chapter, the adopted method of designing a research experiment in the field of learning the Artificial Neural Network of human gait, including measurements, will be presented.

4.1. Assumptions of the experiment

It was assumed that the measurement of human gait will be carried out with the use of cameras. It was assumed that the human walk would follow a given trajectory. The human walk will be recorded by cameras so that it is possible to determine coordinates in space. Therefore, in order to carry out a research experiment, a place of recordings was established with the possibility of recording a human walk from at least two perspectives - the so-called bird and the left profile [21].

In addition, a 1.6 m long path that a human would walk during the experiment was determined. The cameras were placed in fixed places. These were two phones, i.e. Huawei Mate 10 Pro, the camera of which has the ability to record video up to 4K resolution (3 840 x 2 160) at 30 frames per second, and Xiaomi Redmi Note 7, whose maximum recording resolution is Full HD (1 920 x 1 080) at 60 frames per second. In the experiment, both cameras were set to a resolution of 1,280 x 720 at 30 frames per second due to the limitation of the free video editing program [21].

The research experiment was carried out three times. A total of six recordings of human walking were obtained from the point of view of two shots: from the top (three recordings) and from the side (three recordings). Then, the analysis and selection of the obtained recordings was carried out in order to determine the best pair of recordings as a basis for obtaining numerical data on characteristic points on the human body in the Cartesian system (XYZ).

Therefore, in total, in further research, two recordings were used, in which specific projections of human walking were visible, namely: side recording (projection on the XY coordinate system) using the Xiaomi Redmi Note 7 phone and recording from above (projection on the XZ coordinate system) with the Huawei Mate 10 Pro phone.

Then the recordings were edited in order to obtain only the duration of human walking, which was about 4 s. The received recordings were synchronized, and then they were then divided into 30 frames using the scene filter (the film frame interval was set to 3) in the program VLC. As a result of the above-mentioned of technical procedures, 30 photos were obtained from each recording, in which the appropriate human perspective was visible.

All photos have a coordinate system appropriate for a given perspective. On the basis of such prepared projections of human gait, measurements were made for changes: displacement of the left heel (λ_1), displacement of the right heel (λ_2) and displacement of the measurement point of the human body (λ_3).

4.2. Human gait results recorded with a camera

The human gait recorded with two cameras included left heel movement, right heel movement, and the movement of a fixed measurement point at the center of the human body. The obtained results were summarized according to the data structure presented in Table 1.

An example of the methodology of measuring points is shown in Fig. 1 and Fig. 2, which generally boils down to imposing an auxiliary grid in the GIMP program adequate to a given perspective, where one grid is 1x1 [dm] per frames obtained with the VLC Media Player program. Then, using the image coordinates in the GIMP program, the positions of the measurement points were estimated, and then the read data was compiled in a table according to the structure presented in Table 1. The measurements obtained with the first frame are summarized in Table 2.

Table 1. Human gait measurement results. Source: Own measurements made with the Huawei Mate 10 Pro and Xiaomi Redmi Note 7 [26].

	left heel λ_1			right heel λ_2			human body measuring point λ_3		
klatka	X_1	Y_1	Z_1	X_2	Y_2	Z_2	X_3	Y_3	Z_3
1	0,5	0,5	-0,9	0,5	0,5	0,9	1,5	9,6	0,0
2	0,5	0,5	-0,9	0,7	0,7	0,8	1,6	9,6	-0,1
...	...	...	...	...	...	...	...	...	...
30	15,9	0,5	-0,6	15,5	0,5	0,7	16,6	9,6	0,1

Figure 1. Frame 1 from the left profile perspective (XY coordinate system). Markings: red dots - measuring characteristic points, the size of one grid in the auxiliary grid is 1x1 [dm]. Source: Own measurements made with the Xiaomi Redmi Note 7 phone [12, 26].

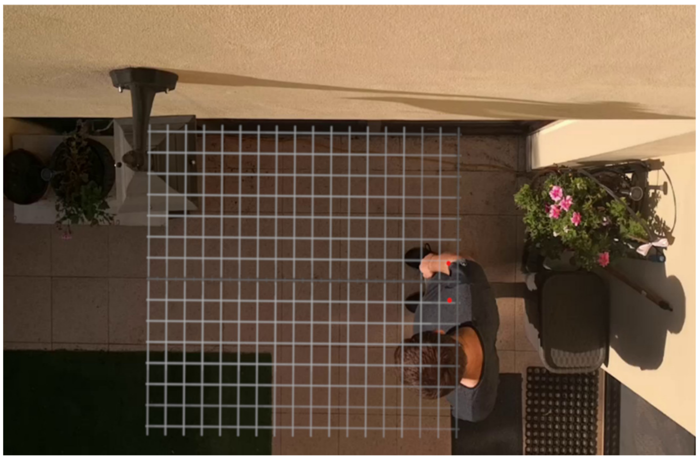

Figure 2. Frame 1 from the bird's perspective (XZ coordinate system). Markings: red dots - measuring characteristic points, the size of one grid in the auxiliary grid is 1x1 [dm]. Source: Own measurements made with the Huawei Mate 10 Pro phone [12, 21].

Table 2. Measurement example obtained with the first frame. Markings in the text. Source: Own measurements made with the Huawei Mate 10 Pro and Xiaomi Redmi Note 7 [12, 21].

left heel λ_1			right heel λ_2			human body measuring point λ_3		
X_1	Y_1	Z_1	X_2	Y_2	Z_2	X_3	Y_3	Z_3
0,5	0,5	-0,9	0,5	0,5	0,9	1,5	9,6	0,0

During the measurements, the convergent perspective in which the shots were taken was taken into account, among others coordinate X_2 i Z_3. The X_2 coordinate therefore seems to be more distant on the X axis than X_1 on the side view, and was therefore verified by the top view. The Z_3 coordinate in the first frame is 0.0 due to the starting position of the human, then the trajectory of the human movement was followed in the following frames to obtain the next values of the Z_3 coordinate.

The coordinates of the measured points of the displacement of the left and right heels were set as the input variables, and the coordinates of the designated points of the moving measurement point of the human body as the output variables. The collected input data was then used to conduct an identification experiment consisting in teaching ANN model of human gait in order to generate a neural model of human gait [21].

4.3. Parameters of designing and learning the artificial neural network of human gait

ANN was designed in the MATLAB and Simulink environment using the Neural Fitting Tool library. The ANN architecture was experimentally established as a Perceptron Artificial Neural Network composed of three layers of neurons, i.e. an input layer with six neurons, an output layer with three neurons and a hidden layer also with 6 neurons. The number of neurons in the hidden layer was determined from the formula determining the geometric mean:

$$w = \sqrt{n \cdot m},$$

where:

m - number of neurons in the input layer,

n - number of neurons in the output layer, which is used in practice to estimate the number of neurons[3], which has been widely described, among others at work [15]. It is assumed that when it is estimated that the model requires two hidden layers of neurons, it is convenient to use the following formulas:

1) for the first hidden layer:

$$w_1 = m \cdot \left(m \cdot \sqrt[3]{\frac{n}{m}} \right)^2,$$

2) for the second hidden layer:

$$w_2 = m \cdot \left(m \cdot \sqrt[3]{\frac{n}{m}} \right).$$

Thus, in the considered case of the designed ANN: m = 6, n = 3, therefore the number of hidden layer neurons is w = 4÷5, so the estimation shows that there should be four or five of them. Experimental studies showed that the number of neurons should be increased by one, so finally six neurons in the hidden layer were assumed.

Three algorithms were used to learn ANN [26]: Levenberg Marquardt's algorithm, Bayesian Regularization algorithm, Scaled Conjugate Gradient algorithm.

4.4. Implementation and teaching of the Artificial Neural Network of human gait

The coordinates of the measured displacement points of the left and right heels were taken as input variables, and the displacement coordinates of the determined measurement point of the human body were adopted as output variables. Thanks to the collected data (30 samples), they were then used to perform neural modeling consisting in designing and teaching ANN model of human movement [16, 19-20]. As a result of the ANN learning process in the MATLAB and Simulink environment using the Neural Fitting Tool, a neural model of human gait was obtained with the following hidden layer weight matrices (W30,6):

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[3] Too many hidden layer neurons cause learning of ANN by heart, and too few hidden layer neurons may cause fatigue in learning ANN, hence the estimation based on the geometric mean was based on the Kolmogorov theory, which results from the properties of approximating functions [15]. Praktycy często stosują także następujacy wzór na wyznaczanie liczby neuronów w warstwie ukrytej: w=(m/2)+n.

$$W_{30,6} = \begin{bmatrix} 0{,}5 & 0{,}5 & -0{,}9 & 0{,}5 & 0{,}5 & 0{,}9 \\ 0{,}5 & 0{,}5 & -0{,}9 & 0{,}7 & 0{,}7 & 0{,}8 \\ 0{,}5 & 0{,}5 & -0{,}9 & 1{,}4 & 0{,}7 & 0{,}7 \\ 0{,}5 & 0{,}5 & -0{,}9 & 2{,}6 & 0{,}7 & 0{,}5 \\ 0{,}5 & 0{,}5 & -0{,}9 & 3{,}7 & 0{,}8 & 0{,}4 \\ 0{,}5 & 0{,}5 & -0{,}9 & 4{,}3 & 0{,}7 & 0{,}5 \\ 0{,}5 & 0{,}6 & -0{,}8 & 4{,}5 & 0{,}6 & 0{,}5 \\ 0{,}8 & 0{,}9 & -0{,}9 & 4{,}5 & 0{,}5 & 0{,}5 \\ 1{,}5 & 1{,}9 & -1{,}0 & 4{,}5 & 0{,}5 & 0{,}5 \\ 3{,}2 & 2{,}0 & -0{,}8 & 4{,}5 & 0{,}5 & 0{,}5 \\ 6{,}1 & 1{,}1 & -0{,}7 & 4{,}5 & 0{,}6 & 0{,}5 \\ 9{,}2 & 0{,}7 & -0{,}6 & 4{,}5 & 0{,}7 & 0{,}5 \\ 10{,}9 & 0{,}7 & -0{,}5 & 4{,}6 & 0{,}9 & 0{,}5 \\ 11{,}0 & 0{,}6 & -0{,}4 & 5{,}1 & 1{,}3 & 0{,}4 \\ 11{,}1 & 0{,}6 & -0{,}4 & 6{,}4 & 2{,}0 & 0{,}3 \\ 11{,}1 & 0{,}5 & -0{,}4 & 8{,}1 & 2{,}0 & 0{,}3 \\ 11{,}1 & 0{,}5 & -0{,}4 & 11{,}3 & 1{,}4 & 0{,}6 \\ 11{,}1 & 0{,}5 & -0{,}4 & 13{,}5 & 0{,}8 & 0{,}4 \\ 11{,}1 & 0{,}6 & -0{,}4 & 15{,}0 & 0{,}9 & 0{,}4 \\ 11{,}2 & 0{,}9 & -0{,}4 & 15{,}4 & 0{,}7 & 0{,}5 \\ 11{,}5 & 1{,}3 & -0{,}3 & 15{,}5 & 0{,}5 & 0{,}7 \\ 12{,}2 & 1{,}8 & -0{,}4 & 15{,}5 & 0{,}5 & 0{,}7 \\ 13{,}5 & 1{,}4 & -0{,}3 & 15{,}5 & 0{,}5 & 0{,}7 \\ 15{,}3 & 0{,}8 & -0{,}2 & 15{,}5 & 0{,}5 & 0{,}7 \\ 15{,}9 & 0{,}5 & -0{,}3 & 15{,}5 & 0{,}5 & 0{,}7 \\ 15{,}9 & 0{,}5 & -0{,}5 & 15{,}5 & 0{,}5 & 0{,}7 \\ 15{,}9 & 0{,}5 & -0{,}6 & 15{,}5 & 0{,}5 & 0{,}7 \\ 15{,}9 & 0{,}5 & -0{,}6 & 15{,}5 & 0{,}5 & 0{,}7 \\ 15{,}9 & 0{,}5 & -0{,}6 & 15{,}5 & 0{,}5 & 0{,}7 \\ 15{,}9 & 0{,}5 & -0{,}6 & 15{,}5 & 0{,}5 & 0{,}7 \end{bmatrix} \tag{1}$$

and the output layer, respectively (W30,3):

$$W_{30,3} = \begin{bmatrix} 1{,}5 & 9{,}6 & 0{,}0 \\ 1{,}6 & 9{,}6 & -0{,}1 \\ 1{,}7 & 9{,}5 & -0{,}1 \\ 1{,}9 & 9{,}5 & -0{,}1 \\ 2{,}1 & 9{,}4 & 0{,}0 \\ 2{,}5 & 9{,}3 & 0{,}0 \\ 3{,}1 & 9{,}2 & 0{,}1 \\ 3{,}9 & 9{,}1 & 0{,}2 \\ 5{,}0 & 9{,}2 & 0{,}4 \\ 6{,}1 & 9{,}2 & 0{,}5 \\ 6{,}9 & 9{,}2 & 0{,}6 \\ 7{,}4 & 9{,}2 & 0{,}6 \\ 7{,}9 & 9{,}1 & 0{,}5 \\ 9{,}2 & 9{,}1 & 0{,}4 \\ 10{,}3 & 9{,}2 & 0{,}3 \\ 11{,}0 & 9{,}3 & 0{,}3 \\ 11{,}6 & 9{,}3 & 0{,}3 \\ 12{,}1 & 9{,}3 & 0{,}2 \\ 12{,}9 & 9{,}2 & 0{,}2 \\ 13{,}5 & 9{,}1 & 0{,}2 \\ 14{,}1 & 9{,}1 & 0{,}3 \\ 14{,}8 & 9{,}0 & 0{,}3 \\ 15{,}1 & 9{,}0 & 0{,}4 \\ 15{,}3 & 9{,}0 & 0{,}4 \\ 15{,}5 & 9{,}1 & 0{,}3 \\ 16{,}0 & 9{,}2 & 0{,}3 \\ 16{,}2 & 9{,}4 & 0{,}2 \\ 16{,}4 & 9{,}5 & 0{,}2 \\ 16{,}5 & 9{,}6 & 0{,}1 \\ 16{,}6 & 9{,}6 & 0{,}1 \end{bmatrix} \tag{2}$$

The Perceptron ANN adopted for learning is therefore a neural network with six inputs corresponding to the current coordinates of the left and right heels and three outputs corresponding to the current position of the coordinates of the displacement point of the human body. The Artificial Neural Network consists of three layers of neurons, i.e. the input layer (with six neurons), the hidden layer (with six neurons) and the output layer (with three neurons) (see Fig. 3) [21].

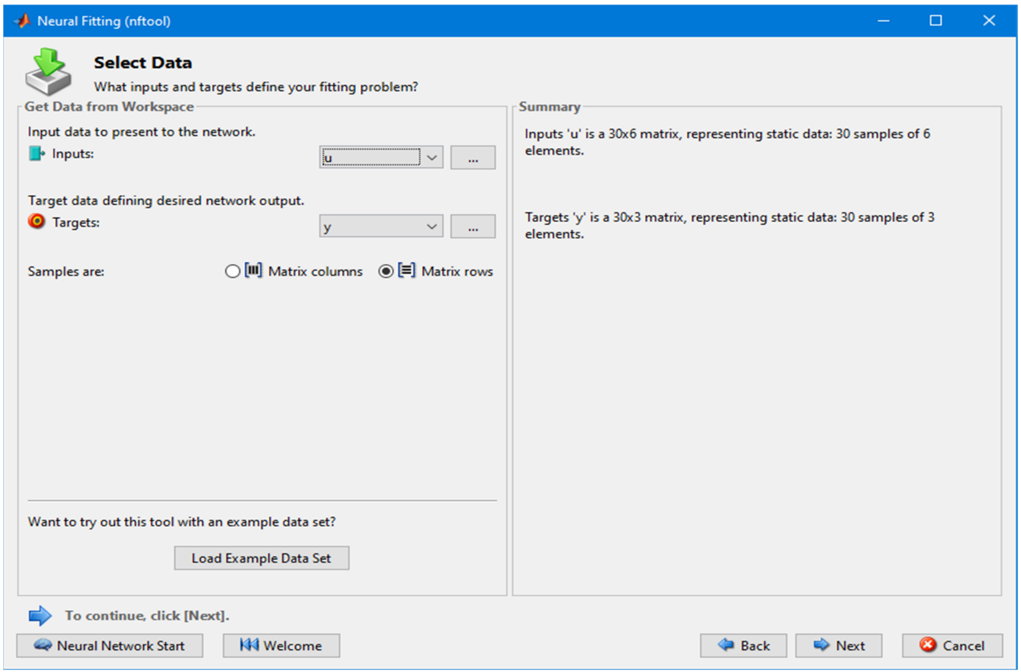

Figure 3. Selection of data intended for ANS learning. Notations: u - input data matrix, y - expected output data matrix. Source: Own study with the use of Deep Learning Toolbox [12, 21].

For learning ANN, data with the structure as in the matrix defined by the relationship (1) and the matrix defined by the relationship (2) were used, which were introduced using the Neural Fitting (nftool) function of the Deep Learning Toolbox library of the MATLAB and Simulink environments (Fig. 4). In the "Input" field, i.e. the input, numerical data were given with the structure as in the matrix defined by the formula (1), and in the "Targets" field, i.e. the value expected at the ANN output, numerical data were given iewith the structure as in the matrix defined by the formula (2) [12, 20].

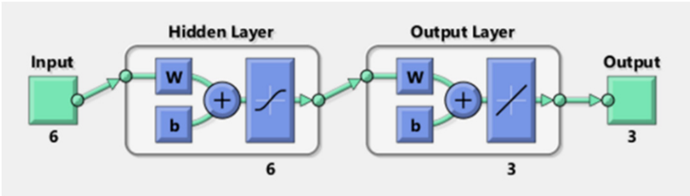

Figure 4. ANN architecture in the notation of MATLAB and Simulink environments. Markings: Input - SSN inputs (here: 6), Hidden Layer - hidden layer (containing 6 neurons), Output Layer - SSN output layer (containing 3 neurons), Output - SSN outputs (here: 3 neurons), **W** - weight matrix, **b** - biase vector. Source: Own elaboration with the use of Deep Learning Toolbox of MATLAB and Simulink environments [21].

5. Algorithms used to teaching the Artificial Neural Network of human gait

5.1. Learning human gait using the Levenberg-Marquardt algorithm

The ANN learning, testing and validation experiment was carried out using the nftool function found in the Deep Learning Toolbox of the MATLAB and Simulink environments. The first learning algorithm used in the experiment was the Levenberg-Marquardt algorithm activated by the trainlm function [16, 19-20]. It is a nonlinear optimization algorithm, which is an iterative algorithm that combines the features of two methods: the steepest descent method and the Gauss-Newton method. The great advantage of the Levenberg-Marquardt algorithm is its fast convergence. For the best learning results, the learning samples were allocated as follows: 80% of the samples were allocated to the network training (23 samples), 15% of the samples were validated (5 samples) and 5% of the samples were allocated to the testing (2 samples). In order to obtain a neural model of human gait, the process of learning the neural network was carried out, which for the above 30 samples lasted 17 epochs (Fig. 5) [12].

The learning process was automatically stopped by the MATLAB program when the validation curve did not show any declines in the process. The best result was obtained from all the selected methods of learning the human gait neural network (Performance: 0.00311, Fig. 5). The learning error decreased from the value of the order of 101 to the value of the order between 10-2 and 10-3, and after 11 epochs it obtained the lowest value of the validation error (Performance: 0.029105, Fig. 6), but it did not show a tendency to further decrease, and even increased so the learning process was stopped [12].

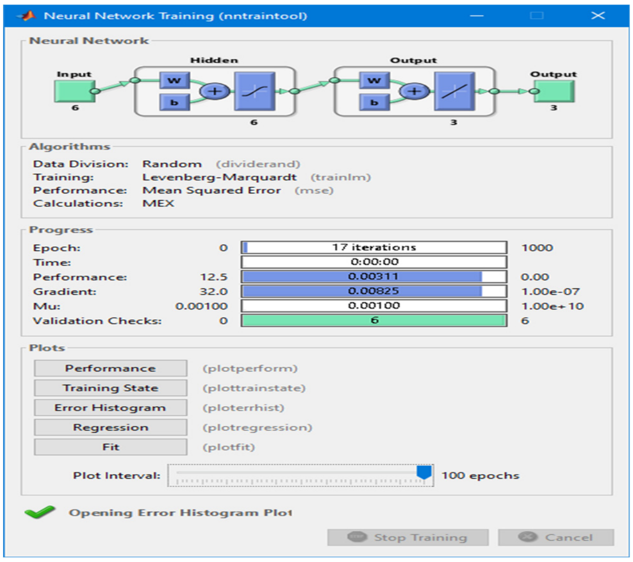

Figure 5. Results of the Perceptron Artificial Neural Network learning process using the Levenberg-Marquardt algorithm. More important symbols: Neural Network - SSN structure, Input - inputs to SSN, Hidden - hidden layer, Output - output layer, Output - outputs from SSN, Source: Own elaboration using Deep Learning Toolbox of MATLAB and Simulink environments [12, 21].

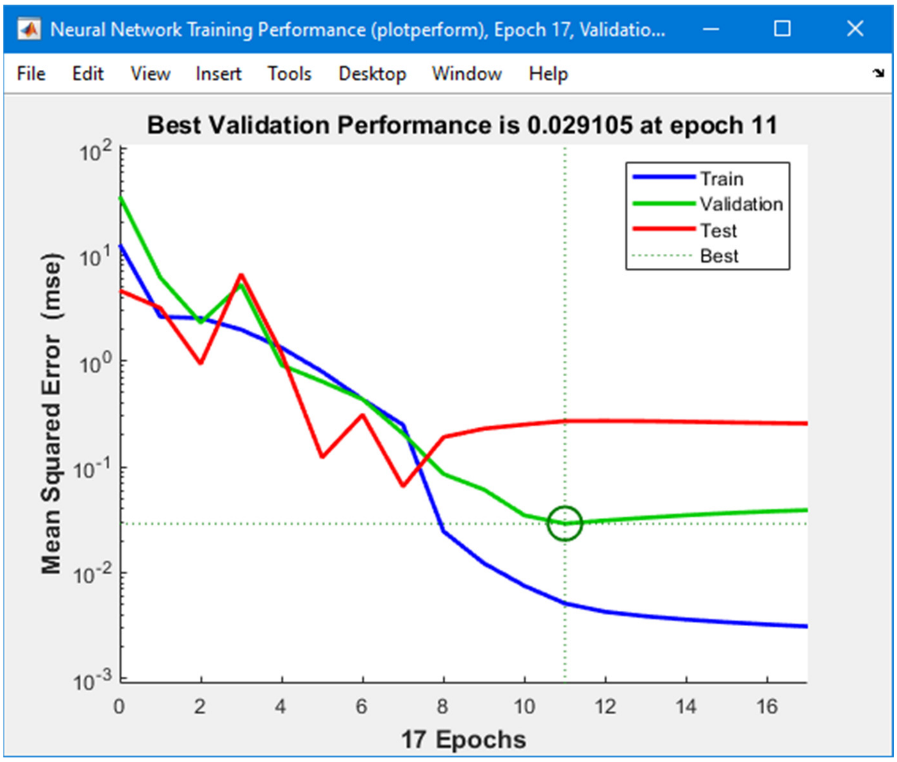

Figure 6. Learning curve of the Perceptron Artificial Neural Network using the Levenberg-Marquardt algorithm. Source: Own elaboration with the use of Deep Learning Toolbox of MATLAB and Simulink environments [12, 21].

5.2. Teaching human gait using the Bayesian optimization algorithm

The second learning algorithm used in the research experiment was the Bayesian optimization algorithm. The trainbr function, which is a function of weights and biases updating with the help of the Bayesian optimization algorithm, was used as the neuron learning function (Fig. 7). The operation of this algorithm is based on an attempt to estimate the optimized function using the values of successive training pairs.

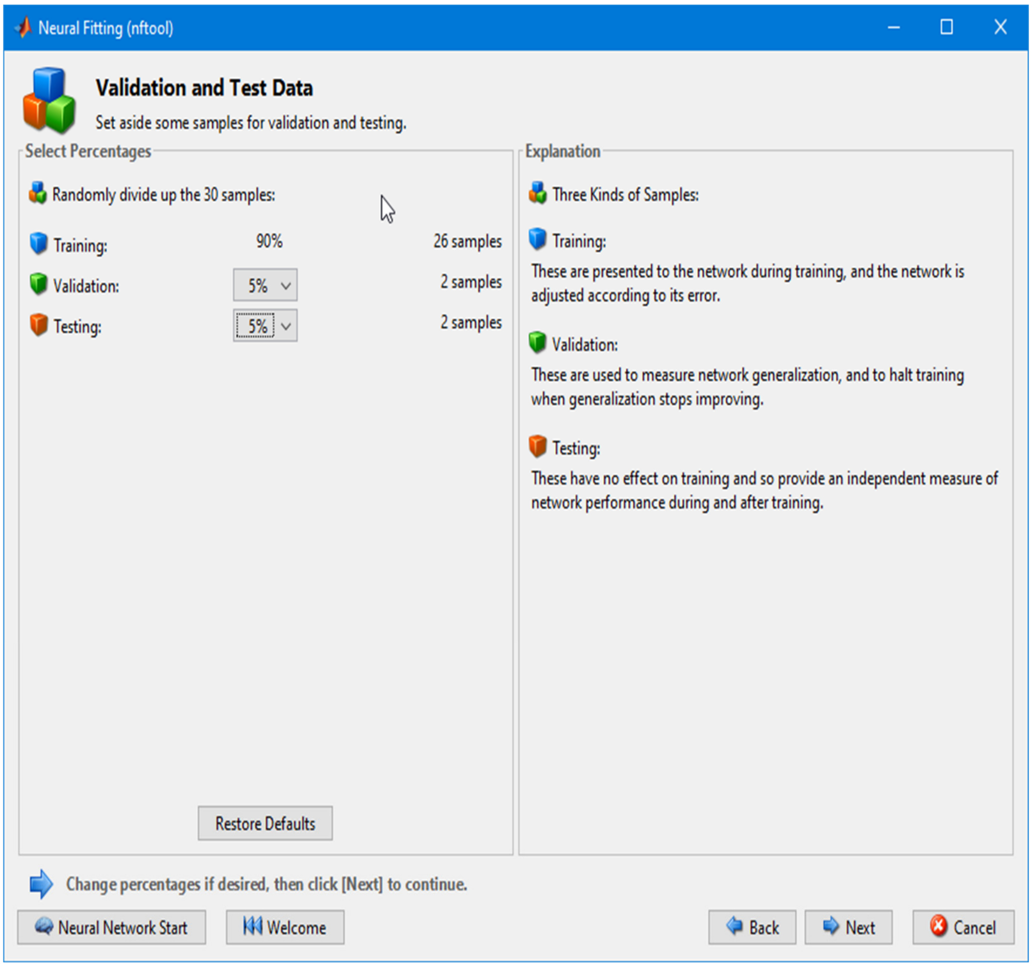

Figure 7. Artificial Neural Network learning parameters using the Bayesian optimization algorithm. Source: Own elaboration with the use of Deep Learning Toolbox of MATLAB and Simulink environments [12, 21].

The algorithm consists of two auxiliary functions. The first is the replacement function whose task is to determine the potential values of the function at the candidate points. The second is the function of acquiring neurons. Its task is to select the point where the maximum of the function is located.

For the best learning results, the learning samples were allocated as follows: 90% of the samples were allocated for network training (26 samples), 5% of the samples were for validation (2 samples), and 5% of the samples were for testing (2 samples).

When this algorithm is used, the validation process does not take place, so in order to improve the learning result, the most was allocated to this stage.

In order to obtain ANN of the human gait model, the ANN learning process was carried out, which for the above 30 samples lasted 344 epochs (Fig. 8). The learning process was automatically stopped by MATLAB when the learning curve did not show any decline in the process. A very good result of teaching the human gait neural network was obtained (Performance: 0.00486).

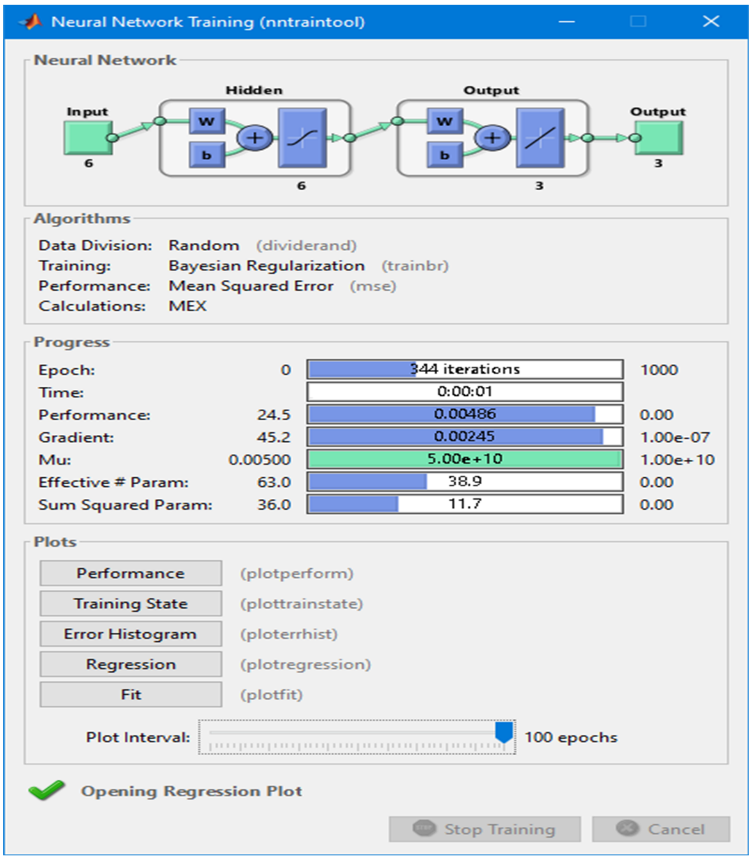

Figure 8. Summary of the Artificial Neural Network learning process using the Bayesian optimization algorithm. Source: Own elaboration with the use of Deep Learning Toolbox of MATLAB and Simulink environments [12, 21].

The learning error dropped from the value of the order of 101 to the value of the order of 10-2, and after 99 epochs it obtained the lowest value of the learning error (Performance: 0.0048578, Fig. 9), but it did not show a tendency for a further decrease [12, 20-21].

5.3. Teaching the Artificial Neural Network of human gait using the coupled gradient algorithm

The conjugate gradient algorithm was used in the third learning algorithm. For this purpose, the trainbr function was used, which is a function of updating weights and biases using the conjugate gradient algorithm (Fig. 10) [12, 16, 19-20].

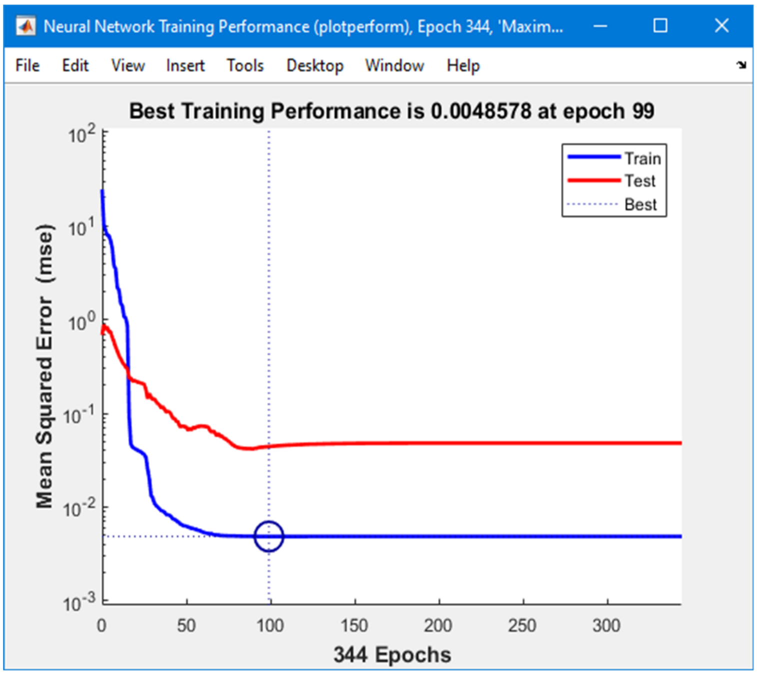

Figure 9. Learning curve of a neural network using the Bayesian optimization algorithm. Source: Own elaboration with the use of Deep Learning Toolbox of MATLAB and Simulink environments [12, 21].

It is based on the assumption that to ensure a proper search of the function domain, the search direction should be created each time not according to the decreasing gradient, but so that it is coupled to the previous gradient value and, if possible, to the previous directions [19-20]. This algorithm is often used because of its relatively fast convergence.

For the best learning results, the learning samples were allocated as follows: 70% of the samples allocated for network training (20 samples), 15% of the samples intended for validation (5 samples), and 15% of the samples intended for testing (5 samples). The above algorithm produced the best results with the default learning sample allocation.

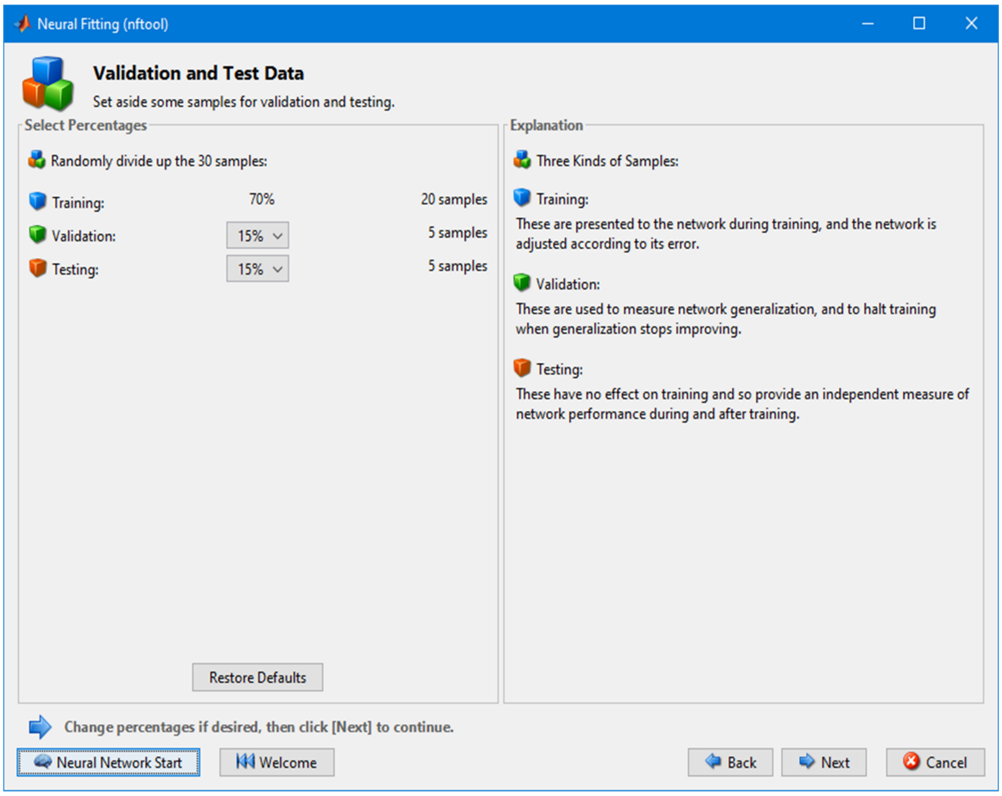

Figure 10. Teaching parameters of the Artificial Neural Network using the coupled gradient algorithm Source: Own elaboration using the Deep Learning Toolbox of the MATLAB and Simulink environments [12, 21].

In order to obtain ANN of the human gait model, the ANN training process was carried out, which for the above 30 samples lasted 17 epochs (Fig. 11). The learning process was automatically stopped when the validation curve showed no declines in the learning process.

The worst result was obtained among the selected methods of teaching the human gait neural network (performance: 0.125). The learning error dropped from the value of the order close to 102 to the value of the order of 10-1, after 11 epochs it obtained the lowest value of the validation error (performance: 0.17813), but it did not show a tendency to further decrease, and even increased, so the learning process was interrupted (Fig. 12) [12, 21, 20].

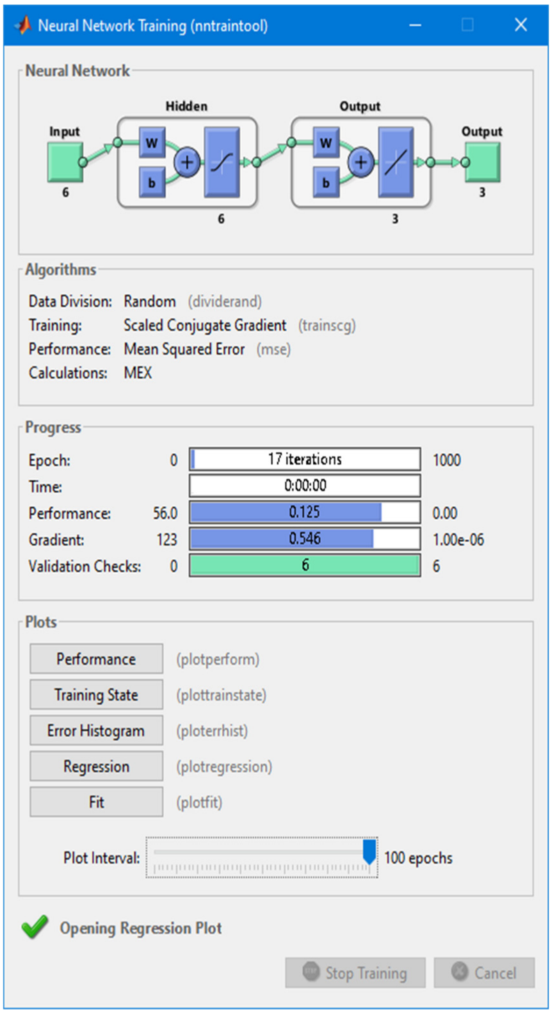

Figure 11. Summary of the Artificial Neural Network learning process using the coupled gradient algorithm. Source: Own elaboration with the use of Deep Learning Toolbox of MATLAB and Simulink environments [12, 21].

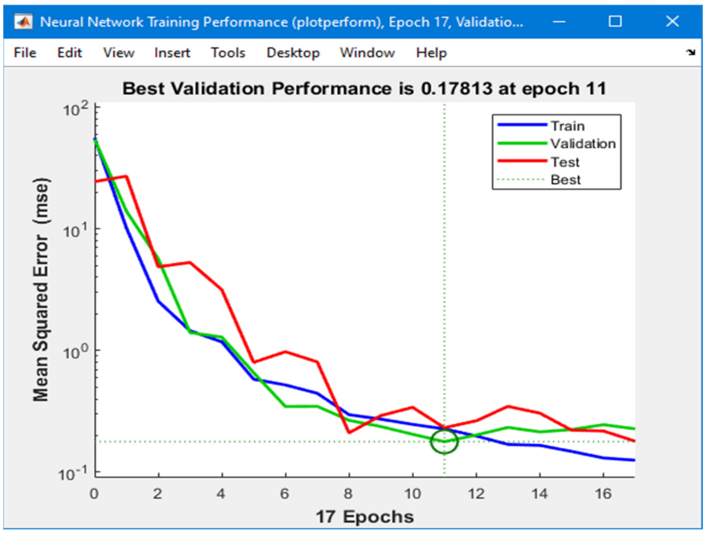

Figure 12. Learning curve of a neural network using the conjugate gradient algorithm. Source: Own elaboration with the use of Deep Learning Toolbox of MATLAB and Simulink environments [12, 20-21].

6. Conclusions and directions for further research

The paper contains selected research results on the design and implementation of the human neural gait model in the MATLAB and Simulink environment with the use of the Deep Learning Toolbox. The subject of the research was placed in the scope of the available literature on the subject, which was tried to be discussed from the point of view of the intended research experiment. Due to the size of the publication, the description has been limited to the necessary minimum, giving up, inter alia, from showing at least selected photos or models of robots, as well as many of their parameters.

In order to conduct an appropriate research experiment, an appropriate environment for practical research was prepared, as well as the method of obtaining information, i.e. with the use of two cameras, was established. It was assumed that human walking would follow a given trajectory. It was assumed that the measured parameters in the experiment will be: input quantities concerning the displacement of the left heel and the displacement of the right heel, and the output quantities concerning the displacement of the human body measuring point in space.

Then, physical research experiments were carried out, as a result of which numerical data were measured in order to use them for teaching and testing the Artificial Neural Network. The Perceptron Artificial Neural Network architecture was used to design the ANN architecture as a model of human neural walk along a given trajectory.

Three algorithms were used to train ANN model of human neural gait: the Levenberg-Marquardt algorithm, the Bayesian Regularization algorithm and the Scaled Conjugate Gradient algorithm. After completing the learning process, each Artificial Neural Network was exported to the MATLAB workspace for use in simulation experiments using Simulink.

The best learning result was achieved by ANN researcher using the Levenberg-Marquardt algorithm, where the learning process lasted 17 epochs. ANN learned with the Bayesian optimization algorithm had the second learning result.

The difference between the learning errors of both of the above-mentioned of neural networks was 0.00311 to 0.00486, where 0 would be a perfect value (it turned out that the learning process using Bayesian optimization was much longer and lasted as many as 344 epochs.

The worst learning result was achieved by ANN trained using the conjugate gradient algorithm. The teaching error of this network is 0.125 and it was definitely higher than for both of the above-mentioned ones. neural network architecture.

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