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Original paper

Use of artificial neural networks for assessing parameters of gait symmetry

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The study attempts to assess gait symmetry based on measurement of vertical component of ground reaction force (GRF) in lower limbs. The aim of the study was to compare the results of gait classification obtained by means of artificial neural networks (ANN) and authors' own quantitative index method. Twenty male and twenty female physiotherapy students participated in the study. Measurements were carried out by means of the Kistler force plate. The profiles of GRF were analysed using ANN which classifies the cases under one of four groups of asymmetry based on suitably prepared training set. Author's own index method was employed for quantitative assessment of the degree of gait asymmetry. The analysis of our symmetry index revealed that the difference between the cases classified by the network as symmetrical and other asymmetrical profiles was significant ($p < 0.001$), which suggests the conformity of both methods.

Key words: *gait symmetry, symmetry indices, artificial neural networks*

1. Introduction

Human natural gait symmetry has been frequently investigated from the aspect of biomechanics. There are a number of reports on this issue, with a wide variety of research methods and the methods for assessing of gait quality [12], [15]. Lack of standards and norms for different parameters which describe gait mechanics is particularly noticeable. Due to attempts to make a quantitative assessment of gait, symmetry indices have grown in number; however, they are not sufficiently versatile to be used for different gait parameters. Symmetry is typically assessed in a quantitative manner based on the ratio of particular kinematic parameters [7] or indices which take into consideration their differences [4]. The analysis of spatial and temporal parameters of gait is legitimate in the investigations of gait with various types of asymmetry, e.g., in patients with hemiplegia caused by stroke. In the case of healthy people, it is necessary to use more sensitive methods based on the profiles of acceleration [9] or ground reaction forces [10]. The comparison of the videographic method with the method of measuring ground reaction forces was presented in the study by WINIARSKI and RUTKOWSKA-KUCHARSKA [16].

Artificial neural networks (ANN) are a method of processing information which is found to be a perfect classification tool. ANN has been previously used for the classification and assessment of free gait [18]. Artificial neural networks are commonly known for their capacity to generalize knowledge and to cope with incomplete data or results which deviate from the dataset. In consideration of high variability of human gait, this char-

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acteristic of ANN can prove useful during classification of experimental data.

The aim of the present study is to compare the results of classification of gait in female and male groups based on the profiles of GRF by means of ANN with the authors' own quantitative index analysis.

2. Material and methods

2.1. Material

Forty physiotherapy students, including twenty males and twenty females, took part in the study. The studied group comprised the subjects who were not ill and did not suffer from any motor organs injuries. Each subject was informed about the goal of the experiment and its course. Means of each variable for female and male groups amounted to: body height: 165.3 ± 5.5 cm and 181.4 ± 6.3 cm; body mass: 57.6 ± 6.5 kg and 75.0 ± 9.2 kg; age: 22.8 ± 2.1 and 22.5 ± 1.5; Body Mass Index (BMI): 21.03 ± 1.6 and 22.79 ± 2.41, respectively. Mean levels of these variables, except for calendar age, differed considerably in the groups ($p < 0.01$ for BMI, $p < 0.001$ for other variables).

2.2. The method of measurement of ground reaction forces

In order to measure GRF during gait, piezoelectric dynamometric force plate was utilized. Force signal was sampled at the frequency of 100 Hz and recorded by means of Bioware®software in digital form in Excel 2003 spreadsheets.

2.3. Course of experiment

During the experiment, all the subjects were wearing sport clothes and the measurement of ground reaction forces was carried out barefoot. Before the measurement, each person performed several trials in order to get familiar with conditions of the measurement. The subjects were supposed to start, at a certain signal, a free gait along the pathway of the measurement track, stepping with one lower limb on the force plate. Every subject performed the free gait twice: each time stepping on the force plate with different leg. Thus, the results consisted of one GRF set for left and one GRF set for right lower limb, for each person.

2.4. Methods of analysis

In order to classify the collected data, a three-layer, nonlinear, multilayer neural network (MLP) was developed by means of Statistica 7.1 software. In order to learn the created ANN, 80 model charts were created to represent theoretical profiles of vertical component of GRF for left and right lower limbs. We wanted our ANN to distinguish four basic types of symmetry/asymmetry, so all the model charts were divided arbitrarily into four groups. Figure 1 presents the examples of model charts for each of the four groups. The criterion of division was the mutual position of the curves in the chart. In each of the charts, a conventional reference point was a model curve which represented the vertical component of GRF in left lower limb. Based on this assumption, four basic options for mutual positions of the curves were determined. The curve which represented right lower limb could be shifted in relation to the reference curve to the right, left, upwards, downwards or they could overlap. According to this division, all the four groups were named, respectively: right-shifted, left-shifted, differences in amplitude, and symmetrical. The data divided in this manner was used as a training set for the created neural network and for the classification of the cases in the study.

At the inputs of the neural network the values of differences between the profiles of left and right lower limbs were given. Thus, the shape and values of the curves were of no value for classification. The network was trained to analyse the character of differences rather than actual values which described the curves and determined their shape.

In order to provide a quantitative assessment of the classification made by the network, a calculation method for determining the similarity of the curves was proposed. Based on the profiles of vertical component of GRF, a specific symmetry index was calculated, which illustrated the similarity of the curves.

In the first step of the analysis, the recorded profiles of vertical component of GRF were presented by means of interpolation as 50 values evenly distributed throughout the whole contact of foot with the ground, just as in the work of BARTON, LEES et al. [1]. Then, reaction force was normalized to body weight (BW).

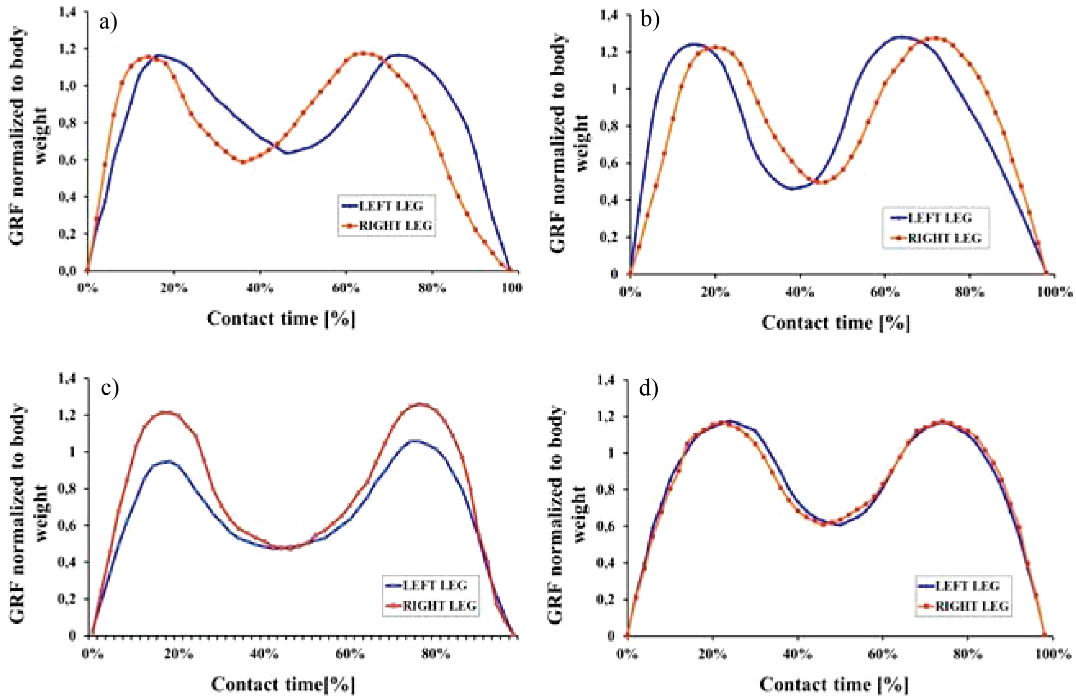

Fig. 1. Model charts of vertical component of GRF for left and right lower limbs, representing a particular gait asymmetry: a – left-shifted, b – right-shifted, c – differences in amplitude, d – symmetrical. The model charts were categorized arbitrarily in order to build ANN network that classifies gait symmetry

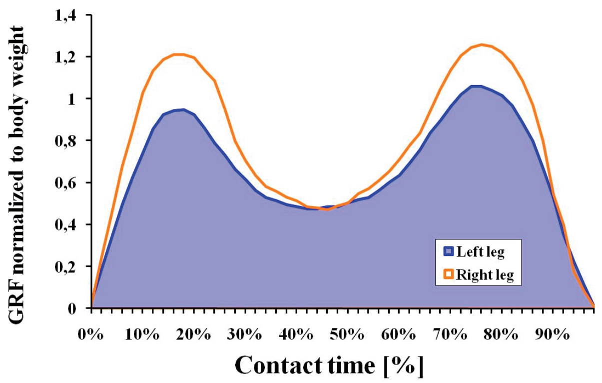

Fig. 2. Curves from the group of model charts termed in the present study "difference in amplitude". They illustrate the asymmetry between the profiles of vertical components of GRF, resulting from the difference in area below the curves

Another step was to determine the average profile of both curves and the profile of differences between both curves. After these calculations, the similarity of curves was assessed with respect to the index popular in the theory of automatic control, expressed as an integral of squared difference of profiles, termed "control error". For the needs of the study, we termed it as the W_1 index. In order to ensure the dimensionlessness of the index, it was normalized to the value of the integral (total) of squared mean profile. The result determined the degree of asymmetry between the curves. Lower values of the index correspond to more "similar" curves. For the profiles recorded as the series of samples, the asymmetry index in profiles adopts the following form:

$$W_1 = \frac{\sum_{1}^{50} (L_i - P_i)^2}{\sum_{1}^{50} (\frac{L_i + P_i}{2})^2}, \qquad (1)$$

where:

i – sample number;

L, P – values of function, respectively, for left and right lower limb.

Although information about the degree of similarity of the curves was obtained, the analysis is not capable of determining how the curves lie in relation to each other. For different arrangements of GRF profiles, it was possible to obtain the same level of a particular index. This method seems to complement the evaluation based on artificial neural networks. Moreover, the symmetry index allows the assessment of classification made by the network by means of statistical tests based on the comparison of means.

3. Results

The neural network had fifty inputs, i.e., exactly as many as the values in each of the GRF profile. At the inputs of the network, all the values for the differences in the profiles for left and right lower limbs were presented. Figure 3 presents the structure of the network.

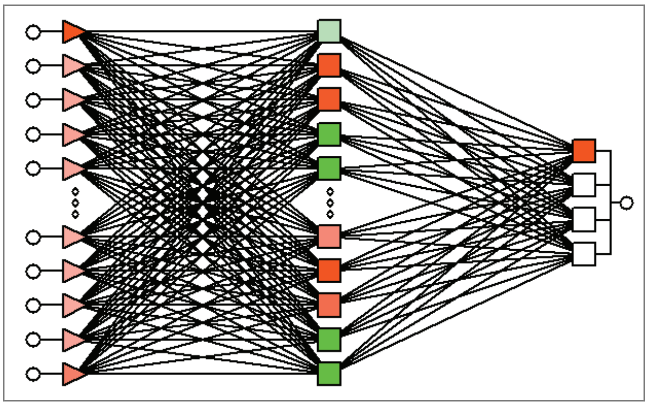

Fig. 3. Structure of the network for classification of free gait symmetry in healthy subjects based on GRF vertical component

The results of the division made by means of the network are presented in table 1.

Table 1. Classification of healthy subjects participating in the study according to the symmetry of profiles for GRF vertical components during free gait, carried out by means of artificial neural network

Group / Gender	Symmetrical gait	Left -shifted	Right -shifted	Differences in amplitude
Women	10 (50%)	6 (30%)	1 (5%)	3 (15%)
Men	14 (70%)	1 (5%)	1 (5%)	4 (15%)

Chi-square test did not reveal ($p > 0.05$) the differences in the fractions of women and men counted in different categories to be statistically significant. Another division was also made for the results above, i.e., the cases categorized as other than under "symmetrical" group were totalled and treated as one group, conventionally termed "asymmetrical". The profile of the group was compared with symmetrical profiles. However, also in this case chi-square test did not reveal significant differences ($p > 0.05$) between the compared fractions. Table 2 presents the indices for the difference in shape between male and female groups, whereas table 3 concerns the profiles categorized as symmetrical and asymmetrical.

Mean levels of W_1 index were compared by means of two-way ANOVA. Two variables were taken into consideration: GENDER and SYMMETRY. Due to the skewness of index distribution, a logarithmic transformation was carried out for the obtained levels of the index. Normality of the variable obtained in this way was confirmed by the Shapiro–Wilk test, both in individual groups and for the whole dataset ($p > 0.20$).

Table 2. Mean levels (±*SD*) and ranges of asymmetry index for GRF profiles for male and female groups

	Men $n = 20$	Women $n = 20$
$\bar{x}$	1.44	2.48
±*SD*	0.94	1.82
Min	0.28	0.52
Max	4.22	7.25
CV [–]	65%	74%

Table 3. Mean levels (±*SD*) and ranges of asymmetry index for GRF profiles categorized as symmetrical and asymmetrical

	Symmetrical $n = 24$	Asymmetrical $n = 16$
$\bar{x}$	1.24	2.92***
±*SD*	0.71	1.82
Min	0.28	0.68
Max	3.18	7.25
CV [–]	57%	62%

*** $p < 0.001$.

The comparison of the subjects with symmetrical profiles to the group of other asymmetrical profiles (SYMMETRY variable) revealed a significant difference in mean levels between the analysed indices ($F_{1,36} = 15.2$; $p < 0.001$). At the same time, no differences in W_1 index between men and women (GENDER variable) were found ($F_{1,36} = 0.78$; $p > 0.05$).

The symmetry was also investigated taking into consideration the time of single support of lower limbs in gait. The Telkk index was employed to determine the level of asymmetry, which has the following form:

$$WA_2 = \frac{P - L}{L} \times 100\% , \tag{2}$$

where:

WA_2 – the Telkk symmetry index,

L, P – the time of a single support of lower limbs during gait, respectively, for left and right lower limb.

Statistical analysis of absolute values of the Telk index was obtained by means of two-way ANOVA. No significant differences were found between men and woman fractions and between symmetrical and asymmetrical cases. Descriptive statistics of the time of single support of lower limbs during gait is presented in table 4.

Table 4. Mean levels (±*SD*) of time of single support of lower limbs during free gait, together with Telkk symmetry index

	Men	Women	Symmetrical	Asymmetrical
Right leg (s)	0.67 ± 0.04	0.60 ± 0.06	0.63 ± 0.07	0.64 ± 0.06
Left leg (s)	0.66 ± 0.03	0.61 ± 0.05	0.63 ± 0.05	0.65 ± 0.04
Telkk index	0.015 ± 0.05	–0.02 ± 0.07	0.00 ± 0.07	–0.02 ± 0.05
Telkk index (absolute values)	0.03 ± 0.04	0.05 ± 0.05	0.04 ± 0.05	0.04 ± 0.04

4. Discussion

The concept of using ANN for imaging gait dysfunctions was presented by BARTON, LEES et al. [1] and BARTON, LISBOA et al. [2]. The goal of the network developed by these authors was to determine individual gait patterns. A high number of variables which describe movement kinematics in each joint in lower limb were used for the analysis. On the other hand, a substantial amount of information can be collected through time-consuming and expensive research, which, from the subjective point of view, might be too absorbing. The advantage of the method discussed in the present study lies in short time of measurements and obtaining the results as well as in a small degree of troubling patients with examinations. The ANN used in the study classifies the cases, which seems to be satisfactory from the clinical point of view. Trained neural network is able to distinguish deviations from normal gait and also classifies the cases into the predefined groups. The information obtained from classification made by ANN is precise if model charts are prepared properly. However, the network developed in order to classify and recognize the patterns cannot assess quantitatively the symmetry/asymmetry of the curves. In order to achieve this goal, W_1 symmetry index was employed in the study. Similar symmetry indices have been presented in the past studies [5], [7]. These indices were expressed either as a ratio of selected values in characteristic points of force profile [5], or as a ratio of the time of a single support or length of steps for both lower limbs [7], [17]. Considerations of mathematical approach to kinematic symmetry of human free gait can also be found in the number of studies [3], [6], [7]. The index proposed in the present study takes into consideration the dynamic aspect of the symmetry and the whole profiles of ground reaction forces under both feet. W_1 index expresses quantitative differentiation of these profiles.

Statistical analysis of the results of the classification performed by neural network did not reveal any significant difference in the fraction of profiles with different type of symmetry/asymmetry in women and men. In view of a relatively low size of the groups participating in the study, it is particularly difficult to decide whether the differences in these fractions are significant or not. Thus, it would be advisable to conduct research with a higher number of subjects. Comparison of (χ^2) cases classified by ANN under a category of "symmetrical" with other profiles (categorized as asymmetrical) did not reveal significant differences in fractions of women and men. However, analogous comparison of mean values of W_1 index in both groups and for both genders (ANOVA) confirmed a significant difference between the groups generated in ANN. Comparison of the fractions of women and men based on index method (ANOVA) did not reveal statistically significant differences. However, the result of the test did not differ considerably from a critical level of the adopted significance. Considering the literature data [14] it is not unlikely that men are characterized by higher symmetry in terms of the measured variable. The Telkk index, as a symmetry measure of a single support time, did not discriminate between genders as well as between symmetrical and asymmetrical groups distinguished by ANN. This lack of correspondence between two parameters (time and force) is ambiguous. This might be a result of a compensation process. The ranges of the asymmetry observed in normal gait, based on the profiles of the vertical component of GRF, can provide a supplement to considerations of the asymmetry of the centre of pressure between the foot and the ground presented in a study by JELEŃ, WIT et al. [8].

Since statistical analysis of the level of W_1 index revealed a significant difference between the profiles recognized by ANN as symmetrical and asymmetrical, it can be argued that the asymmetry connected with the force acting on lower limbs occurs even in healthy subjects. Although the levels of the index are merely a quantitative measure of asymmetry, the

ANN results describe the character of this asymmetry. The method presented in this study seems to be sensitive enough to detect the laterality of free gait in healthy subjects. These results might suggest the existence of functional differences between left and right lower limb, one of which is more responsible for stabilization and carrying body weight, whereas the other one performs driving functions. The existence of this relationship has been confirmed by previous studies [11]. Similar interpretations are reported by SADEGHI, ALLARD et al. [13], although these authors emphasize that there are also a number of studies which have not confirmed functional differences between the limbs related to lateralization.

The attempt to utilize ANN in this study for assessing gait symmetry can provide a solid basis for the designing of future investigations. Collecting sufficient research material would allow us to make up a set of force profiles and to train the network for the recognition of proper gait profiles. It would be also useful to develop the standards or at least reference values of quantitative W_1 index. It could be also considered whether the process of self-training would not be a better way to acquire the information about gait symmetry by the network. Based on a number of ground reaction force profiles, neural network would be trained for the recognition of proper gait and it would even recognize several options of proper gait patterns. The results of the present study and their interpretation suggest that ANNs have substantial potential for the assessment of variables which characterize human gait.

In summary, it is noteworthy that the results obtained during the investigations and the analysis of these results allowed several significant conclusions to be formulated. Based on analytical methods, a common asymmetry of gait (which manifests itself in uneven load on the left and right lower limbs) can be demonstrated in healthy subjects. Artificial neural networks might become a perfect tool for the analysis of symmetry during screening. No differences were found in the asymmetry of free gait between women and men. The conformity of the classification made by means of an artificial neural network with the assessment made on the basis of index analysis was demonstrated. The results of the study can be useful for determining the ranges of physiological gait asymmetry.

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