

# Computational gait analysis for post-stroke rehabilitation purposes using fuzzy numbers, fractal dimension and neural networks

P. PROKOPOWICZ<sup>1\*</sup>, D. MIKOŁAJEWSKI<sup>1,2</sup>, K. TYBUREK<sup>1</sup>, and E. MIKOŁAJEWSKA<sup>3</sup>

<sup>1</sup>Institute of Mechanics and Applied Computer Science, Kazimierz Wielki University, Kopernika 1, 85-074 Bydgoszcz, Poland

<sup>2</sup>Neurocognitive Laboratory, Centre for Modern Interdisciplinary Technologies, Nicolaus Copernicus University in Toruń, Poland

<sup>3</sup>Department of Physiotherapy, Ludwik Rydygier Collegium Medicum in Bydgoszcz, Nicolaus Copernicus University in Toruń, Poland

**Abstract.** Computational gait analysis constitutes a useful tool for quantitative assessment of gait disturbances, improving functional diagnosis, assessment of treatment planning, and monitoring of disease progress. There is little research on use of computational gait analysis in neurorehabilitation of post-stroke survivors, but current evidence on its clinical application supports a favorable cost-benefit ratio. The research was conducted among 50 adult people: 25 of them after ischemic stroke constituted the study group, and 25 healthy volunteers constituted the reference group. Study group members were treated for 2 weeks (10 neurorehabilitation sessions). Spatio-temporal gait parameters were assessed before and after therapy and compared using a novel fuzzy-based assessment tool, fractal dimension measurement and gait classification based on artificial neural networks. Measured results of rehabilitation (changes of gait parameters) were statistically relevant and reflected recovery. There is good evidence to extend its use to patients with various gait diseases undergoing neurorehabilitation. However, methodology for properly conducting and interpreting the proposed assessment and analysis procedures, providing validity and reliability of their results remains a key issue. More objective clinical reasoning, based on proposed novel tools, requires further research.

**Key words:** computational analysis, spatio-temporal gait parameters, fuzzy analysis, gait classification, disorder recognition.

## 1. Introduction

Stroke is regarded as one of the leading causes of death and long-term dependence in both developed and developing countries. Its occurrence in young adult and mid-adult people is increasing. Young adult is defined with the range of 20–39 years of age, while the range of 40–64 years represents the mid-adult group. Moreover it influences almost all aspects of their lives, including the ability to learn, work, live independently and bring up their children. On the other hand, recovery potential of young stroke survivors may be greater and requires dedicated studies aiming at looking for optimal ways of rehabilitation. Stroke, influencing gait function, decreases mobility of patients, and subsequently their independence, activities of daily living, and life in the community. Spatio-temporal gait parameters in post-stroke patients may be mildly-to-severely compromised. Their objective assessment may be a useful way to assess general efficiency of gait function restoration through a neurorehabilitation. Scientists and clinicians still look for novel computational approaches allowing for simple, cheap, semi-automated patient-oriented gait analysis. The NDT-Bobath method for adults is one of the most popular therapeutic methods in neurorehabilitation, including gait relearning [1, 2]. But current studies concerning NDT-Bobath use in post-stroke

gait rehabilitation generate methodological concerns related to study/treatment fidelity and measurement [3]. Although the NDT-Bobath method is well known, its theory and clinical practice are not well documented in literature, especially its randomized controlled trials (RCTs). There are only a few studies concerning application of computational tools in this area [4, 5]. Lack of objective evidences generates problems with application of evidence-based medicine in everyday clinical practice. Our ultimate goal is a family of novel, mobile, semi-automated tools for clinical gait analysis purposes, especially for supplementary initial assessment of patient functioning and further cyclic re-assessment of the rehabilitation process. The scientific objective of this paper was to apply novel computational intelligence tools based on fuzzy numbers, fractal dimension, and classification based on artificial neural networks to compare immediate results of post-stroke gait rehabilitation using Bobath versus the conventional approach in young and mid-adults. According to our best knowledge, fuzzy systems, fractal dimension and ANNs have not been used simultaneously in gait analysis, especially in deficits resulting from stroke, one of the three most prevailing civilization' diseases.

This paper is structured as follows. Firstly, assumptions of the clinical study whose results are analysed, the main concepts and principles are all recalled in Section 2. Next, Section 3 describes algorithms of the processing of outcomes using fuzzy systems. Then, Section 4 presents rules of fractal analysis and classification based on artificial neural networks. Section 5 shows results of the analysis. After that a discussion and comment for the result are presented, followed by conclusions.

\*e-mail: piotrekp@ukw.edu.pl

Manuscript submitted 2019-06-27, revised 2019-11-24, initially accepted for publication 2019-11-29, published in April 2020

## 2. Material and methods

The study was conducted among 50 young adult patients (aged 26–55 years) after ischemic stroke, both males and females. Patients were randomly assigned to one of the treatment groups: study group (treated with NDT-Bobath method,  $n = 25$ ) and reference group (treated with conventional method,  $n = 25$ ). Inclusion criteria were age above 18 y.o. and below 55 y.o., time after ischemic stroke from 4 weeks to three years lack of contraindications to rehabilitation and the ability to walk. Exclusion criteria were age below 18 y.o. or above 55 y.o., contraindications to rehabilitation and lack of the ability to walk. Randomization type: sequentially numbered containers. Containers were similar in appearance, equal in weight, and tamper-proof – no detectable differences between containers were observed. The aforementioned inclusion and exclusion criteria protocol was formulated to include a sample reflecting the normal population of young post-stroke survivors.

Table 1  
Patients' overall profile

Parameter	Study group $n = 25$ (100%)	Reference group $n = 25$ (100%)
Age [years]: min	26	28
max	55	55
mean	43.5	44
SD	3.99	3.47
quartile 1 (Q1)	36	38
median (Q2)	45	46
quartile 3 (Q3)	49	50.5
Gender:		
F	14 (56%)	13 (52%)
M	11 (44%)	12 (48%)
Side of paresis:		
L	12 (48%)	13 (52%)
R	13 (52%)	12 (48%)
Time after CVA [weeks]:		
min	4	4
max	156	156
mean	74.25	67.18
SD	16.32	14.33
quartile 1 (Q1)	28.5	31.5
median (Q2)	69.5	66
quartile 3 (Q3)	106	102

Study design was a randomized prospective before-after study (BAS). Ten metres walking test in the front of camera was used to assess main spatio-temporal gait parameters: gait velocity, normalized gait velocity, cadence, normalized cadence, stride length and normalized stride length. Anterior superior iliac spine (ASIS) to medial malleolus distance measured in each patient for assessing leg length discrepancy was used to normalize the aforementioned values. Previous methodological problems were eliminated thanks to the following organization of study:

- each patient took part in the same number of sessions (10) of the therapy for 2 weeks (ten days of therapy),

- rehabilitation program was conducted by a therapist with more than 15 years of experience in neurorehabilitation, moreover their NDT-Bobath skills were confirmed by basic and advanced courses in NDT-Bobath for adults according to the International Bobath Instructors Training Association (IBITA) requirements,
- to assess rehabilitation effects (reflected by change of parameters), measurements were performed in every patient twice: on admission (before therapy) and after last session of therapy,
- all measurements were administered by a physical therapist, subjects completed the measures in identical standardized conditions,
- computational analysis was applied by an interdisciplinary team of scientists.

The aforementioned description appears to be important for replication purposes or compartmental studies due to significant remarks mentioned by Paci [6], including definition and course of the NDT-Bobath approach in gait rehabilitation according to the original book “NDT-Bobath method in neurorehabilitation of adults” [7]. Conventional gait rehabilitation was defined as therapeutic approach without use of specific methods such as NDT-Bobath or Proprioceptive Neuromuscular Facilitation (PNF). All the data in this study were collected and stored using Microsoft Excell 2013 software. The Shapiro-Wilk test was used to assess normality of the distribution. Where available, mean, standard deviation (SD), quartile 1 (Q1), median (quartile 2, Q2), quartile 3 (Q3), minimum value (Min), the maximum value (Max) were calculated to show the results of this study. Parametric t-student test and non-parametric Wilcoxon's test as far as U Mann-Whitney and chi-squared tests were used to compare scores. Change of parameters was calculated as results of subtraction. Spearman's rho was used to assess correlations among changes of parameters. Effect size and confidence interval was added. Statistical analysis was performed using IBM SPSS Statistics 21. The difference was statistically significant at  $p > 0.05$ . Computational analysis was performed using Matlab software. Novel computational intelligence tools were used in this study based on 1) fuzzy numbers, 2) fractal dimension, and 3) classification based on artificial neural networks (ANN) to compare immediate results of post-stroke gait rehabilitation using Bobath versus conventional approach in young and mid-adults. Freely given written informed consent was obtained from every patient prior to the study. The study was conducted in accordance with the Declaration of Helsinki, the guidelines for Good Clinical Practice (GCP) and the agreement of the local bio-ethical committee.

## 3. Fuzzy system for gait features assessment

The quality of gait is very difficult for formal precise definition. It depends on the general public and varies depending on the group which we consider to be the norm in the terms of gait. If the precise model is out of reach, we can use the tools for imprecise information processing – fuzzy systems. Researchers

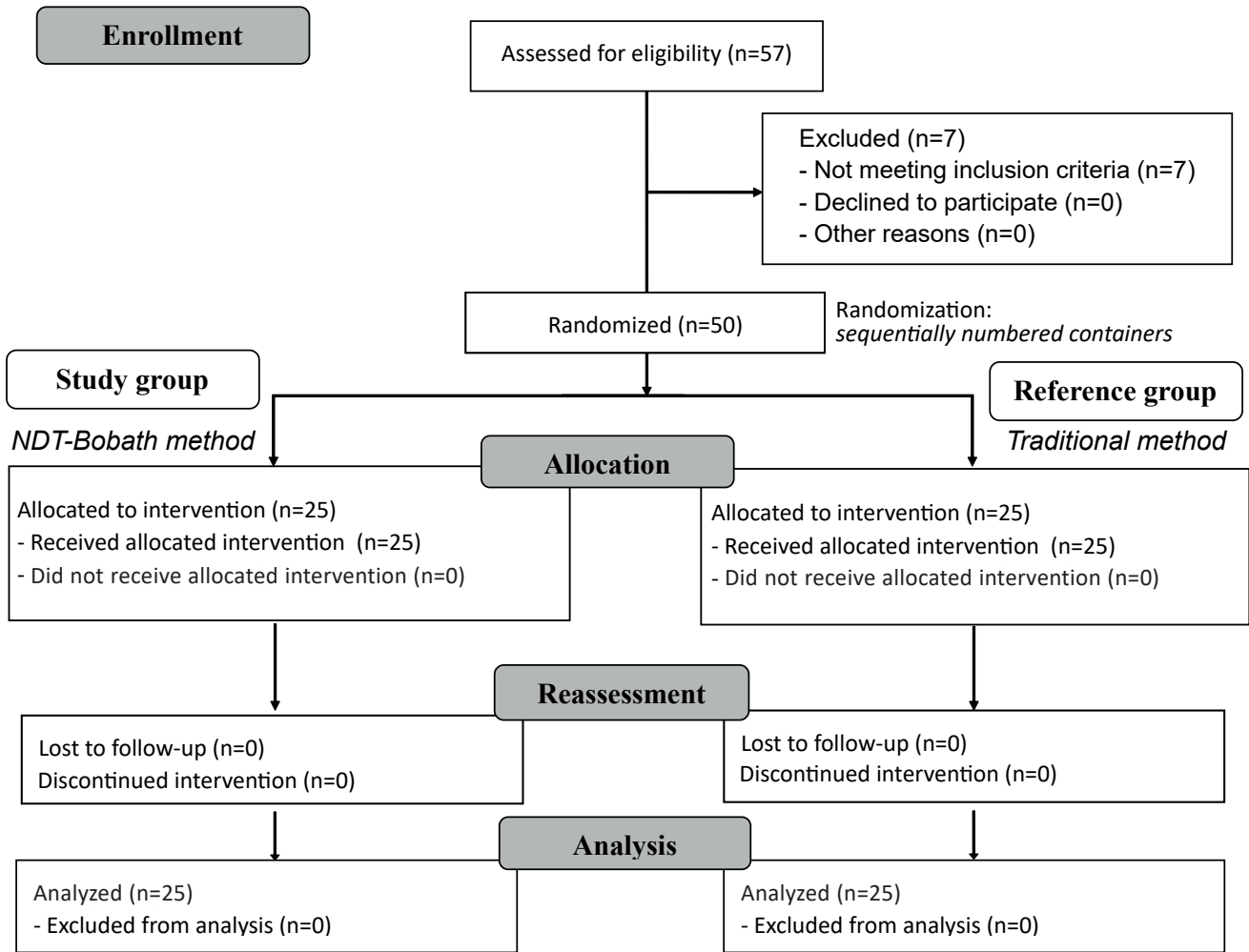


Fig. 1. CONSORT patient's flow chart diagram

often use this tool in the face of linguistically formulated data/information gathered from experts, e.g. [8–10]. Fuzzy logic allows for transferring a linguistic description into a computer algorithm. As there is a lack of a mathematical model of the evaluation, fuzzy systems seem to be a good direction. A linguistic model of rules, which describes expected evaluations depending on input values, comes from the experience health scientists/therapists who work with post-stroke patients.

The main advantage of the fuzzy systems are the flexibility, intuitiveness and clarity of rules that are easy to describe linguistically.

To obtain the results for this paper, one fuzzy system was defined for each gait parameter. General features of these fuzzy systems are as follows:

- singleton fuzzyfication,
- implication operator – MIN,
- defuzzyfication uses the Middle of Maxima (MOM) method.

Measuring gait quality has a certain specificity. Its character is not that of monotonic dependence. Bad quality is a parameter of being either too low or too high. Therefore each variable that represents gait parameter consists of three linguistic values: 'too low', 'proper' and 'too high'. The output variable – quality

– consists of two values: 'good' and 'bad'. So the rules follow the patterns below:

1. IF the parameter is 'too low' THEN quality is 'bad',
2. IF the parameter is 'proper' THEN quality is 'good',
3. IF the parameter is 'too high' THEN quality is 'bad'.

The output is simply defined on the [0; 1] interval, therefore the results are measured as the scale from 0 to 1.

The fuzzy set representing the ideal value for each gait parameter is constructed from the data given for the reference group – people without a stroke. Each of them is a triangular fuzzy set (see LR fuzzy sets notation in [11]) and is determined on the all the available data. For example, let's look at the *Proper Gait Velocity* – (proper-GV) set:

$$\text{proper - GV} = \Lambda(x; x_{mean} - 2 \cdot \Delta_L, x_{mean}, x_{mean} + 2 \cdot \Delta_R) \quad (1)$$

where  $\Delta_L = x_{mean} - x_{min}$ ,  $\Delta_R = x_{max} - x_{mean}$ ,  $x_{min}/x_{max}/x_{mean}$  – the minimum/maximum/mean value of the Gait Velocity parameters for the available data about healthy (non post-stroke) people.

The range of linguistic variable is defined as interval  $[0; 2 \cdot x_{mean}]$ . It is enough to cover all the available data for healthy and post-stroke people. There are two another fuzzy sets which represent ‘bad’ quality of gait. The ‘ $bad_{100-low}^{GV}$ ’ and ‘ $bad_{100-high}^{GV}$ ’ are trapezoidal fuzzy sets (see fuzzy intervals [11]), defined by four parameters as follows:

$$\begin{aligned} bad_{100-low}^{GV} &= \Pi(x; x_0, x_0, x_{mean} - 2 \cdot \Delta_L, x_{mean}), \\ bad_{100-high}^{GV} &= \Pi(x; x_{mean}, x_{mean} + 2 \cdot \Delta_R, \\ &\quad 2 \cdot x_{mean}, 2 \cdot x_{mean}), \end{aligned} \quad (2)$$

where  $x_0 = MIN(0, x_{mean} - 2 \cdot \Delta_L)$ .

#### 4. Gait pattern classification and fractal parameter application for gait features assessment

The quality of gait and high velocity of gait are opposite parameters. Thus we need to measure both of them simultaneously. This may be useful both in traditional rehabilitation as well as in novel robotized forms of rehabilitation, despite it still being very difficult to formally precisely define it. As a general rule, we may assume one, well-known from many sport disciplines: technique first, then achievements. This means that during the first period of rehabilitation (gait re-education) proper technique of walking (including propulsion) constitutes a key value. Thus velocity might not be so high, but cadence and stride length should be most important. Proper gait rehabilitation allows to increase its velocity step by step without worsening its technique. This means that better gait technique allows for slower development of the rest of parameters, but it also results in further improved performance, lower energy consumption and higher abilities not possible for people with poor technique. How we can measure technique of gait? In our study we do it in a twofold manner:

1. we use ANN-based gait classification to avoid pathological gait, e.g. hemiplegic one,
2. we use fractal dimension to compare values for subsequent steps (i.e. uniformity of gait, influence of fatigue, etc.) and left side to right side gait (i.e. to avoid hemiplegic gait).

For fractal dimension measurement we used a box counting method, the purpose of which is to consider the average number (noted  $N(r)$ ) of square boxes with fixed side length  $r$ , necessary to cover the image, considered as a surface in  $R^2$  space. Fractal dimension  $D \in R^2$  space has values from 1 to 2. Generally, if fractal object  $S$  is divided into  $N$  objects similar to  $S$  in homothety  $1/r$ , fractal dimension is:

$$D = \frac{\log N}{\log \frac{1}{r}} \quad (3)$$

For that we estimated  $P(m, r)$ , i.e. the probability that one box of size  $r$ , centred on an arbitrary point of surface, contains

$m$  points of the set, where  $N_p$  constitutes the number of possible points in the cube.

$$\forall r, \sum_{m=1}^{N_p} P(m, r) = 1 \quad (4)$$

The estimate of the average number of disjointed boxes (i.e. those sufficiently isolated to avoid the effect of overlapping) necessary to cover the surface is expressed by the following value:

$$N(r), \sum_{m=1}^{N_p} N(m, r) = \sum_{m=1}^{N_p} \frac{P(m, r)}{m} \quad (5)$$

Thus fractal dimension is given by the estimate made by means of the least squares method of the slope of the group of dots ( $\log(r), -\log(N(r))$ ), obtained with boxes of increasing size  $r$ . Box sizes are chosen experimentally to minimize error of fractal dimension assessment.

Both aforementioned techniques, ANN-based and fractal dimension, required dedicated algorithms, based on analysis of video recording of walking people and assessment of time/distance features of subsequent heel to floor contact moments.

Improvement of gait regularity was reflected in the value of fractal parameters. A relatively simple and fast algorithm to determine fractal dimensions by box counting was used because it is accurate, and less dependent on data-specific curve fitting criteria. For more advanced applications Higuchi’s algorithm [12] may be used.

Three-layer artificial neural network for gait classification purposes. Multi-layer perceptrons (MLPs) combination classifiers were used to categorize gait data into two categories; healthy and patient with gait deficit. A more advanced gait type classification method, using a smart insole with various sensor arrays, may be based on deep neural networks.

The aforementioned analysis is not computationally expensive, but still complex, and can be used rather only as a ‘‘close to real-time’’ solution. We used professional computational tools, but basic calculation requirement was that of time-efficiency.

The aforementioned approach still needs improvements and further development. It has to constitute a compromise between complexity and cost on the one hand and possibility of application on mobile devices (portability), integration into eHealth Internet of Things technologies, and simplicity on the other. According to our requirements, it should be a screening test rather than an advanced laboratory tool.

## 5. Results

The results of measuring gait parameters are presented in Tables 2–4.

Statistically significant and favorable changes in gait velocity, cadence and stride length as far as their normalized values have been observed in both groups. The aforementioned changes were higher in the study group.

Table 2  
 Changes of parameters in both groups

Value		Parameter							
		Gait velocity	Cadence	Stride length	Normalized gait velocity	Normalized cadence	Normalized stride length	Fuzzy parameter	Fractal parameter
Changes in study group	Mean	0.30	20.12	0.49	0.13	0.10	0.61	0.03	0.06
	SD	0.08	4.05	0.16	0.04	0.02	0.22	0.01	0.02
	Min	0.02	5	0.10	0.02	0.02	0.16	-0.10	0.01
	Q1	0.15	11.22	0.22	0.06	0.05	0.35	0.00	0.03
	Median	0.28	20	0.44	0.10	0.08	0.58	0.04	0.04
	Q3	0.42	36	0.70	0.15	0.17	0.89	0.12	0.05
	Max	0.70	59	1.26	0.27	0.33	1.12	0.21	0.06
Changes in reference group	Mean	0.18	11.17	0.22	0.06	0.07	0.22	0.04	0.04
	SD	0.04	3.02	0.07	0.02	0.02	0.07	0.01	0.01
	Min	0.01	2	0.05	0.03	0.01	0.06	-0.1	0.01
	Q1	0.05	7	0.10	0.04	0.03	0.10	0.02	0.03
	Median	0.12	12.5	0.17	0.05	0.06	0.18	0.03	0.04
	Q3	0.31	23.5	0.26	0.11	0.15	0.25	0.12	0.05
	Max	0.65	52	0.59	0.24	0.32	0.53	0.32	0.06
p-value		0.012	0.029	0.032	0.029	0.022	0.017	0.04	0.017
Effect size		1.90	2.51	2.19	2.21	1.50	2.39	2.21	1.50
Confidence interval		1.12–2.60	1.63–3.28	1.37–2.92	1.39–2.95	0.77–2.17	2.54–3.15	1.39–2.95	0.77–2.17

 Table 3  
 Correlations of changes in study group

	Gait vel.	Cadence	Stride length	Normalized cadence	Normalized stride length	Normalized gait velocity	Fuzzy parameter	Fractal parameter
Gait velocity	–	0.602 p = 0.001	0.617 p = 0.015	0.887 p = 0.003	0.657 p = 0.019	0.477 p = 0.009	n.s.	n.s.
Cadence		–	0.611 p = 0.007	0.512 p = 0.014	0.707 p = 0.003	n.s.	n.s.	n.s.
Stride length			–	0.529 p = 0.005	0.492 p = 0.007	0.779 p = 0.012	n.s.	n.s.
Normalized gait velocity				–	0.622 p = 0.007	0.387 p = 0.042	0.832 p = 0.004	0.625 p = 0.017
Normalized cadence					–	n.s.	0.511 p = 0.015	0.734 p = 0.002
Normalized stride length						–	0.523 p = 0.007	0.454 p = 0.012
Fuzzy parameter							–	0.611 p = 0.021
Fractal parameter								–

n.s. – not significant

 Table 4  
 Correlations of changes in the reference group

	Gait vel.	Cadence	Stride length	Normalized cadence	Normalized stride length	Normalized gait velocity	Fuzzy parameter	Fractal parameter
Gait velocity	–	0.512 p = 0.011	0.599 p = 0.004	0.887 p = 0.003	0.657 p = 0.019	0.477 p = 0.009	n.s.	n.s.
Cadence		–	0.552 p = 0.012	0.512 p = 0.014	0.707 p = 0.003	n.s.	n.s.	n.s.
Stride length			–	0.529 p = 0.005	0.492 p = 0.007	0.779 p = 0.012	n.s.	n.s.
Normalized gait velocity				–	0.622 p = 0.007	0.387 p = 0.042	0.789 p = 0.005	0.688 p = 0.017
Normalized cadence					–	n.s.	0.567 p = 0.015	0.777 p = 0.009
Normalized stride length						–	0.534 p = 0.010	0.478 p = 0.009
Fuzzy parameter							–	0.611 p = 0.011
Fractal parameter								–

n.s. – not significant



Moderate and high correlations between changes of assessed spatio-temporal gait parameters have been observed both, in the study (see Table 3) and reference (Table 4) groups. However, the results were lower in the reference group. No important injuries or unwanted effects were observed. ANN analysis proved high accuracy of prediction.

## 6. Discussion

Generalisability (external validity, applicability) of the trial findings: statistically significant and favorable changes in all measured parameters have been observed, reflecting larger effectiveness of the NDT-Bobath approach than that of the conventional approach. Further studies are planned as randomized trials on larger samples, with long-term rehabilitation-related gait changes to be also assessed. We also work on improved, more objective research methodology, e.g. assessing the asymmetry pattern.

Another future challenge is the assessment of balance training, where study by Şimşek and Çekok [13] showed that Nintendo Wii training is as effective as NDT-Bobath in patients with sub-acute stroke, and more objective measurements such as sEMG or balance tensometric platform. Next step will be studies on comprehensive application of the NDT-Bobath method (not only in gait rehabilitation). Cognitive state as well as the number of patients with aphasia, hemianopia, etc. may influence outcomes of the therapy as far as the time from stroke onset to introducing patients' to the study is concerned.

Compartmental studies concerning NDT-Bobath method in gait rehabilitation for adults have been rare so far. Study by Krukowska et al. [14] showed that NDT-Bobath for improving the balance of the body is a more effective method of treatment in comparison with the PNF method. Moreover in stroke patients, the effectiveness of the NDT-Bobath method did not depend on hand paresis. We should take into consideration that the study by Lee et al. [15] showed relative influence of standing balance and trunk balance on gait ability. Value of the NDT-Bobath method in gait rehabilitation of adult stroke survivors was showed in several studies by Mikołajewska [16–19]. Their evidence was limited due to the lack of a reference group. Current results are similar to the aforementioned ones but constitute significant evidence supporting common use of the NDT-Bobath method in neurorehabilitation of gait disorders in post-stroke adults. Individualized exercise NDT-Bobath-based rehabilitation improves trunk function, balance, and walking ability in stroke patients more than conventional therapy (exercises) [20]. Evidence concerning improvement in walking long distances (also on different surfaces and around obstacles) after 3-week NDT-Bobath rehabilitation was provided by Benito Garcia et al. [21]. International Classification of Functioning, Disability and Health (ICF) proved its usefulness as a tool for assessment of functioning. Meanwhile Motor Relearning Program is more effective than the NDT-Bobath approach in acute rehabilitation of patients with a stroke [22].

Interpretation is consistent with the results, balancing benefits and potential injuries, and it considers other relevant

evidence: most of current research concerns elderly people or whole groups of adults, not only young adults [23]. Rehabilitation potential of young adults may be increased as compared with older patients, but it requires further research. There is also place for combined use of NDT-Bobath and research on various mixed/eclectic approaches as a step toward patient-tailored therapy. Combining valuable rehabilitative procedures, including NDT-Bobath, into an individual training package was described by Chen and Shaw [24]. Improvement of gait performance in a group of patients with post-stroke hemiparesis treated with the NDT-Bobath method is similar to outcomes of robot-supported therapy [25].

Therapy based on the NDT-Bobath concept supported by task practice is more effective than task practice alone [26]. Injection of botulinum toxin type A combined with NDT-Bobath therapy showed improvements at lower limb spasticity, gait and balance in post-stroke patients. The aforementioned improvements were larger than for the use of botulinum toxin type A alone [27]. Results of NDT-Bobath therapy are similar to that of the NDT-Bobath method combined with tapping therapy with plum blossom needle at the key points. Both showed efficiency in hemiplegic spasticity following cerebral infarction [28]. Another manner for integration of the NDT-Bobath approach with traditional Chinese medicine was described by Zhang et al. [29]. Methodological concerns were recently addressed in [30] but only concerning 6MWT and 12MWT. There is a need for similar review of clinical gait assessment tools for the more severely disabled, including tests provided under natural conditions (including at patient's home).

The proposed computational tools proved their usability and efficacy even in the cases where changes due to rehabilitation process are subtle. Study limitations (sources of potential bias and/or imprecision): the study described assessed only immediate results of rehabilitation on a limited sample of patients ( $n = 40$ ), and may thus be regarded a pilot study. What is new in the study as compared to those of other scientists: eliminating methodological concerns related to study/treatment fidelity and measurement, including a comparably detailed level of professional preparation of the therapist, allowing for replication of the study.

Many studies demonstrated the superiority of machine learning methods in diagnosis [31]. We should focus on flexible features of the proposed computational solution, allowing for application in many environments, including basic use by general practitioners and physical therapists. Such approach may divide patients into two groups: healthy people and patients who require further diagnosis, usually more accurate one. Outcomes concerning trends may immediately influence the method and pace of rehabilitation. Additionally, we know that improvement of gait quality might not be reflected immediately in traditional gait analysis outcomes – but improvement of gait regularity may be reflected in the value of fractal parameter. Results in treating low gait quality with simultaneous multi-feature gait analysis is crucial for quick recovery (i.e. in the area of velocity). Further studies may also incorporate deep learning and deep neural networks (DNN), which may significantly increase performance in classification or pattern recognition. Optimizing network parameters, avoiding over-fitting and ensuring good generalization

abilities are necessary [32, 33]. Potential application of the proposed algorithm on mobile devices makes future 3D gait pattern reconstruction and visualization easier [34].

Indirect results of further studies will take the form of comparative analysis of validity and reliability of the proposed computational tools, coordination of trends within gait recovery processes, taking into consideration both patients' functional status on admission, place and severity of the damage, the set of rehabilitation interventions used and resultant better understanding of gait recovery and its underlying mechanisms. The collected case data bases may allow for more accurate calibration of algorithms and more precise inquiries, because there is a need of a whole new approach in basic clinical gait analysis using mobile devices within novel possibilities given by the Internet of Things. The ultimate solution may allow for simple, cheap gait analysis even for runners or nordic-walkers, allowing for very early detection of gait disorders.

## 7. Conclusions

The NDT-Bobath method may be regarded as a more effective form of gait post-stroke rehabilitation in young adults as compared to conventional rehabilitation. Statistically significant and favorable changes in gait velocity, cadence and stride length, as far as their normalized values are concerned, observed. Moderate and high correlations between changes the spatio-temporal gait parameters being assessed have been observed in both groups.

The computational intelligence methods proposed constitute not only the next step from traditional statistical analysis of biomedical data sets. It also constitutes another breakthrough due to the novel approach to studies conducted by interdisciplinary teams and to the data analysis methods included. This is possible due to the following features:

- it allows for extraction of additional features not supported by traditional statistical analysis,
- it reflects even subtle changes in observed health status of patients more effectively, especially due to advanced trend analysis,
- it constitutes a bidirectional manner of reasoning since it allows for better asking of clinical questions, the answers to which may be more effectively analysed as part of computational analysis.

Thus co-operation may be more fruitful for both sides:

- clinicians, because they are able to more precisely assess the clinical status of the each patient and effects of therapy, and also to provide a more advanced decision-making process, based on evidence-based medicine paradigm,
- IT specialists, because they may prove advantages and disadvantages of the computational analysis based on outcomes of experimental studies, and provide semi-automated fine tuning for better performance. The aforementioned approach may prove purely novel for clinical data sets, not self-standing but forming part of a wider computational system, supporting diagnosis and treatment within everyday clinical practice.

## REFERENCES

- [1] P. Klimkiewicz, A. Kubsik and M. Woldańska-Okońska, "NDT-Bobath method used in the rehabilitation of patients with a history of ischemic stroke", *Wiad. Lek.* 65(2), 102–107 (2012).
- [2] B.J. Kollen, S. Lennon, B. Lyons, L. Wheatley-Smith, M. Schepfer, J.H. Buurke, J. Halfens, A.C. Geurts, and G. Kwakkel, "The effectiveness of the bobath concept in stroke rehabilitation", *Stroke* 40(4) (2009).
- [3] J. Vaughan-Graham, C. Cott, and F. V. Wright, "The bobath (NDT) concept in adult neurological rehabilitation: what is the state of the knowledge? a scoping review. part II: intervention studies perspectives", *Disability and Rehabilitation* 37(21), 1909–1928 (2014).
- [4] P. Prokopowicz, E. Mikołajewska, D. Mikołajewski, and P. Kotlarz, "Analysis of temporospatial gait parameters", In P. Prokopowicz, J. Czerniak, D. Mikołajewski, Ł. Apiecionek and D. Ślezak (eds.), *Theory and Applications of Ordered Fuzzy Numbers: A Tribute to Professor Witold Kosiński*, 289–302. Springer International Publishing, Cham (2017).
- [5] P. Prokopowicz, D. Mikołajewski, E. Mikołajewska, and P. Kotlarz, "Fuzzy system as an assessment tool for analysis of the health-related quality of life for the people after stroke", In L. Rutkowski, M. Korytkowski, R. Scherer, R. Tadeusiewicz, L.A. Zadeh and J. M. Zurada (eds.), *Artificial Intelligence and Soft Computing*, 710–721. Springer International Publishing, Cham (2017).
- [6] M. Paci, "Physiotherapy based on the bobath concept for adults with post-stroke hemiplegia: a review of effectiveness studies", *Journal of rehabilitation medicine* 35(1), 2–7 (2003).
- [7] E. Mikołajewska, "Metoda NDT-Bobath w neurorehabilitacji osób dorosłych", Wydawnictwo Lekarskie PZWL (2012).
- [8] J. Kacprzyk and S. Zadrozny, "Towards human consistent data driven decision support systems using verbalization of data mining results via linguistic data summaries", *Bull. Pol. Ac.: Tech.* 58(3), 359–370 (2010).
- [9] M. Jasiński, P. Majtczak, and A. Malinowski, "Fuzzy logic in decision support system as a simple human/internet of things interface for shunt active power filter", *Bull. Pol. Ac.: Tech.* 64(4), 877–886 (2016).
- [10] A. Sukhanov, S. Kovalev, and V. Stýskała, "Fuzzy interpretation for temporal-difference learning in anomaly detection problems", *Bull. Pol. Ac.: Tech.* 64(3), 625–632 (2016).
- [11] D. Dubois, *Fuzzy Sets and Systems: Theory and Applications. Mathematics in Science and Engineering*, Elsevier Science (1980).
- [12] F.C.-D. la Torre, J. I. González-Trejo, C.A. Real-Ramírez, and L.F. Hoyos-Reyes, "Fractal dimension algorithms and their application to time series associated with natural phenomena", *J. Phys. Conf. Ser.* 475, 012002 (2013).
- [13] T.T. Şimşek and K. Çekok, "The effects of nintendo WiiTM-based balance and upper extremity training on activities of daily living and quality of life in patients with sub-acute stroke: a randomized controlled study", *Int J Neurosci* 126(12), 1061–1070 (2015).
- [14] J. Krukowska, M. Bugajski, M. Sienkiewicz, and J. Czernicki, "The influence of NDT-bobath and PNF methods on the field support and total path length measure foot pressure (COP) in patients after stroke", *Neurol Neurochir Pol* 50(6), 449–454 (2016).

- [15] K.B. Lee, S.H. Lim, Y.D. Kim, B.I. Yang, K.H. Kim, K.S. Lee, E.J. Kim, and B.Y. Hwang, "The contributions of balance to gait capacity and motor function in chronic stroke", *Journal of Physical Therapy Science* 28(6), 1686–1690 (2016).
- [16] E. Mikołajewska, "Normalized gait parameters in NDT-bobath post-stroke gait rehabilitation", *Open Medicine* 7(2) (2012).
- [17] E. Mikołajewska, "The value of the NDT-Bobath method in post-stroke gait training", *Adv Clin Exp Med* 22(2), 261–272 (2013).
- [18] E. Mikołajewska, "Associations between results of post-stroke NDT-Bobath rehabilitation in gait parameters, ADL and hand functions", *Adv Clin Exp Med* 22(5), 731–738 (2013).
- [19] E. Mikołajewska, "NDT-bobath method in post-stroke rehabilitation in adults aged 42–55 years – preliminary findings", *Polish Annals of Medicine* 22(2), 98–104 (2015).
- [20] M. Kılınc, F. Avcu, O. Onursal, E. Ayvat, C.S. Demirci, and S.A. Yildirim, "The effects of bobath-based trunk exercises on trunk control, functional capacity, balance, and gait: a pilot randomized controlled trial", *Topics in Stroke Rehabilitation* 23(1), 50–58 (2016).
- [21] M.B. Garcia, M.Á.A. Arratibel, and M.E.T. Azpiroz, "The bobath concept in walking activity in chronic stroke measured through the international classification of functioning, disability and health", *Physiother Res Int* 20(4), 242–250 (2014).
- [22] B. Langhammer and J.K. Stanghelle, "Can physiotherapy after stroke based on the bobath concept result in improved quality of movement compared to the motor relearning programme", *Physiother Res Int* 16 (2), 69–80 (2010).
- [23] Q. Tang, L. Tan, B. Li, X. Huang, C. Ouyang, H. Zhan, Q. Pu, and L. Wu, "Early sitting, standing, and walking in conjunction with contemporary bobath approach for stroke patients with severe motor deficit", *Topics in Stroke Rehabilitation* 21(2), 120–127 (2014).
- [24] J.-C. Chen, "Progress in sensorimotor rehabilitative physical therapy programs for stroke patients", *World Journal of Clinical Cases* 2(8), 316 (2014).
- [25] G. Taveggia, A. Borboni, C. Mulé, J. H. Villafañe, and S. Negri, "Conflicting results of robot-assisted versus usual gait training during postacute rehabilitation of stroke patients", *Int. J. Rehabil. Res.* 39(1), 29–35 (2016).
- [26] K. Brock, G. Haase, G. Rothacher, and S. Cotton, "Does physiotherapy based on the bobath concept, in conjunction with a task practice, achieve greater improvement in walking ability in people with stroke compared to physiotherapy focused on structured task practice alone? a pilot randomized controlled trial", *Clin Rehabil* 25(10), 903–912 (2011).
- [27] S. Gallagher, C.P. Phadke, F. Ismail, and C. Boulias, "Physical therapy for an adult with chronic stroke after botulinum toxin injection for spasticity: A case report", *Physiotherapy Canada* 67(1), 65–68 (2015).
- [28] F. Wang, L. Zhang, J. Wang, Y. Shi, and L. Zheng, "Efficacy on hemiplegic spasticity treated with plum blossom needle tapping therapy at the key points and bobath therapy: a randomized controlled trial", *Zhongguo zhen jiu= Chinese acupuncture & moxibustion* 35(8), 781–784 (2015).
- [29] X. Zhang, R. Qi, and J. Yan, "Clinical research on post-stroke hemiplegia treated with the optimized rehabilitation program of integrated chinese and western medicine", *Zhongguo zhen jiu= Chinese acupuncture & moxibustion* 33(12), 1113–1117 (2013).
- [30] N.M. Salbach, K.K. O'Brien, D. Brooks, E. Irvin, R. Martino, P. Takhar, S. Chan, and J.-A. Howe, "Considerations for the selection of time-limited walk tests poststroke: a systematic review of test protocols and measurement properties", *Journal of Neurologic Physical Therapy* 41(1), 3–17 (2017).
- [31] Q. Zhao, Y. Qiu, G. Zhou, and A. Cichocki, "Comparative study on the classification methods for breast cancer diagnosis", *Bull. Pol. Ac.: Tech.* (2018).
- [32] M. Grochowski, A. Kwasigroch, and A. Mikołajczyk, "Selected technical issues of deep neural networks for image classification purposes", *Bull. Pol. Ac.: Tech.* 67(2), 363–376 (2019).
- [33] A. Cichocki, T. Poggio, S. Osowski, and V. Lempitsky, "Deep learning: Theory and practice", *Bull. Pol. Ac.: Tech.* 66(6), 757–759 (2018).
- [34] G. Anbarjafari, R. Haamer, I. Lüsi, T. Tikk, and L. Valgma, "3d face reconstruction with region based best fit blending using mobile phone for virtual reality based social media", *Bull. Pol. Ac.: Tech.* 67(1) (2019).